BEYOND THE MILKY WAY

From an official photograph, United States Army Air Service.

Airplane view of Mount Wilson Observatory.

BEYOND THE MILKY WAY

BY

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WITH
NUMEROUS ILLUSTRATIONS

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TO

H. M. G.

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PREFACE

With the exception of the first chapter, for which material was gathered chiefly in Egypt and England, the contents of this book relate to the recent work of the Mount Wilson Observatory. The three chapters have recently appeared as articles in *Scribner's Magazine*, in continuation of the series already represented in book form by "The New Heavens" and "The Depths of the Universe."

I owe my thanks for most of the illustrations to the Mount Wilson Observatory and the astronomers whose names appear in the captions, and to Mr. Ferdinand Ellerman, who prepared the material for reproduction. I am indebted to the Royal Society of London, the Yerkes Observatory of the University of Chicago, the Metropolitan Museum of Art, the United States Army Air Service, the Superintendent of Government Printing, Calcutta, Messrs. Ginn & Co., the Librairie Hachette, Messrs. Macmillan & Co., the Oxford University Press, and to others cited in the captions or the text, for the use of illustrations. I also wish to express my appreciation of assistance of various kinds received from Dr. Walter S. Adams, Dr. James H. Breasted, Professor H. F. Newall, Dr. Robert A. Millikan, Professor Frederick H. Seares, Dr. Charles G. Abbot, Dr. J. A. B. Scherer, Dr. Henry Norris Russell, Dr. Edwin Hubble, Dr. Seth B. Nicholson, Dr. Edison Pettit, and the late Dr. Nichols's associate, Dr. Tear.

G. E. H.

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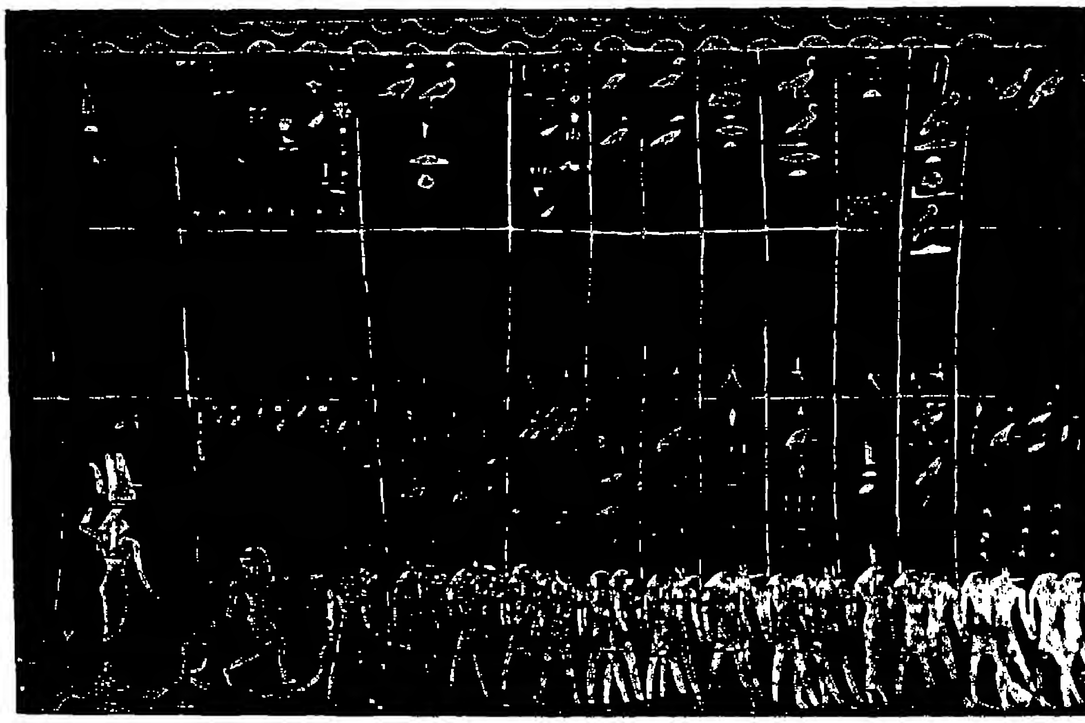
THE ORIENTAL ANCESTRY OF THE TELESCOPE

"Temp era il principio del mattino
E il sol montavan su con quelle stelle
Ch'eran con lui quando l'amor divino
Mosse da prima quelle cose belle."
—DANTE, "Inferno."

THE first astronomer was primitive man, who ordered his life by the stars. The daily course of the sun and his cheering return after the cold and darkness of the night; the advance from winter to summer, as the arc of the sun's path rose toward the zenith from its lowest limit in the south; the changing phases of the moon and the terrifying darkness of eclipses; the serene majesty of the midnight sky, sparkling with stars and rotating in slow and stately measure about the celestial pole: these and the wandering planets, the sudden meteors, and the rare comets, little noticed by modern dwellers in the glare of cities but of compelling splendor in the transparent atmosphere of the ancient world, deeply impressed the mind and the imagination of prehistoric man. Even in the Stone Age observations of the sun and moon are suggested by certain circles and crescents in neolithic art, replacing the animal portraiture of paleolithic times.

Thus early began the study of astronomy, starting from conceptions which, though simple and familiar, imply inductive thought, and aided by the clarity and definiteness of ideas of space and figure,



By courtesy of the Metropolitan Museum of Art. From a photograph by Mr. Harry Burton.

Fig. 1. List of stars and constellations in the Sepulchral Hall of Seti I (about B. C. 1309), in the Valley of the Tombs of the Kings.

On the extreme left is the star Sothis or Sirius, identified with Isis, whose heliacal rising originally marked the beginning of the new year. Next, to the right, is Orion.

time and number, motion and recurrence. Unlike the invisible electrons, whirling in their orbits within the atom, or the microscopic organisms so vital in biological research, the brilliant members of the celestial host pursued their course before every eye, and invited study by their oft-repeated revolutions. Great laws of nature were open to discovery by any

observer, armed only with clear vision and persistence of purpose. Hence it was that astronomy became the pioneer of the sciences, leading the way, not only in Egypt and Babylonia, but in Greece and the Moslem world, in the revival of research against the forces of mediævalism, and in the beginnings of modern investigation in Italy, France, England, and the United States.

ASTRONOMY IN EGYPT

In Egypt, where civilization arose, three influences were dominant: the sun, supreme as the great god Ra; the stars, abode of the blessed; and the Nile, fructifier of the fields. The earliest peasants based their year on the annual inundation of the Nile, and the date of its beginning became a matter of practical concern. This happened to coincide very nearly with the heliacal rising of Sothis (Sirius), whose first appearance on the horizon in advance of the sun was thus taken to announce the new year. Systematic observations began so far back that the first fairly reliable date in history, given by Breasted as the beginning of the year 4241 B. C., was thus fixed by this star.

The ancient Egyptian, in all the phases of his life, was severely practical. Like the Roman, but in sharp contrast with the Greek, he had little intellectual curiosity and in general he cared nothing whatever for the problems of science. Breasted has recently found, in the only known medical papyrus which is not merely a mass of magical formulas, that

the old Egyptian author occasionally exhibits some interest in the symptoms of cases designated by himself as incurable. Robbins and Karpinski have also given "definite indications of real progress in

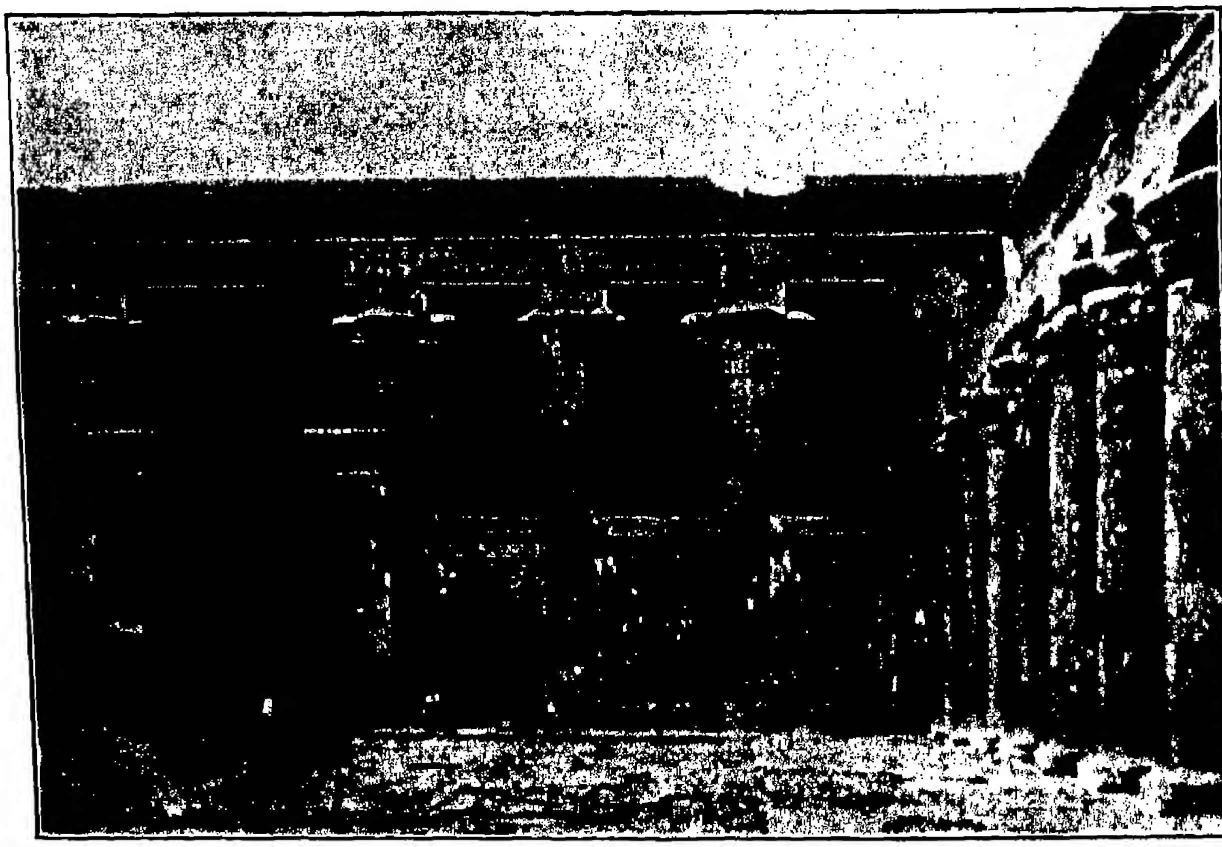


Fig. 2. The Temple of Edfu.
The astronomer priests of Egypt made their observations from the summits of the temples.

mathematical thinking among the Egyptians." * But, if we may judge from existing knowledge, these are individual instances, contrary to the national habit, lone exceptions that prove the rule. The priests, always powerful and sometimes in complete control of the government, directed a large part of

* Nichomachus of Gerasa, University of Michigan Studies, Macmillan, 1926, p. 9.

the activities of the Pharaoh and people toward their own aggrandizement, as we may see from the fact that almost the only surviving structures on the Nile are enormous temples and tombs, their walls covered with the grotesque images of the gods and the complex ritual of the underworld. Monumental art was cultivated under rigorous control, almost exclusively for theological and mortuary purposes. Under such circumstances we cannot expect to find that the Egyptians contributed greatly to the progress of astronomy as a science.

However, the needs of common life and the daily routine and annual festivals of the temples demanded a reliable calendar and the subdivision of time, which could be provided only by astronomical observations. The priests became astronomers, and at a surprisingly early date, as we have seen, the opening of the year was fixed by the heliacal rising of Sirius. Contrary to the practice of the Babylonians, whose calendar was based upon the phases of the moon, the Egyptians determined their year by the annual return of the sun to a fixed point in the heavens, and measured its duration as three hundred and sixty-five days. With such beginnings, much might have been expected of a truly progressive people. But, as in the history of Egyptian art, which never surpassed the high level attained in the earliest dynasties, we find but few signs of scientific advance four thousand years later, when the Egyptians passed on their slight intellectual possessions to the Greeks.

For observations of the stars, the summit of a temple, commanding a free horizon under the cloudless skies of Egypt, admirably served the purposes of the astronomer priests. The eye was all that was needed to fix the year by observations of heliacal risings, but instruments for the determination of shorter time divisions were invented at a very early period. Through a fortunate discovery, the Oriental Institute of the University of Chicago has recently come into the possession of one of the earliest known instruments for observing the stars, made (as the inscription states) by no less a person than the Pharaoh Tutenkhamon, "with his two hands."

BREASTED'S DISCOVERY OF TUTENKHAMON'S TRANSIT INSTRUMENT

After returning from Egypt in the spring of 1923 Professor Breasted and I spent a month at the Villa Palmieri, near Florence, as guests of Mr. James W. Ellsworth. Following his work at the tomb of Tutenkhamon, which I had been fortunate enough to see, Breasted was then writing of his previous discovery on the upper Euphrates of a remarkable Roman mural decoration, since published in his "Oriental Forerunners of Byzantine Painting." Through the kindness of Doctor Giorgio Abetti, director of the Royal Astrophysical Observatory, we were enabled to observe the sun, moon, Jupiter, and Saturn with two of Galileo's original telescopes, preserved in the Galileo Museum at Florence, and attached for this purpose to the equatorial telescope

at Arcetri. In a future article I shall endeavor to describe this attempt to see the heavens with Galileo's eyes. After these observations with the earliest of telescopes, Breasted went to London, where he discovered at a shop of a well-known dealer in antiquities a far older astronomical instrument, the

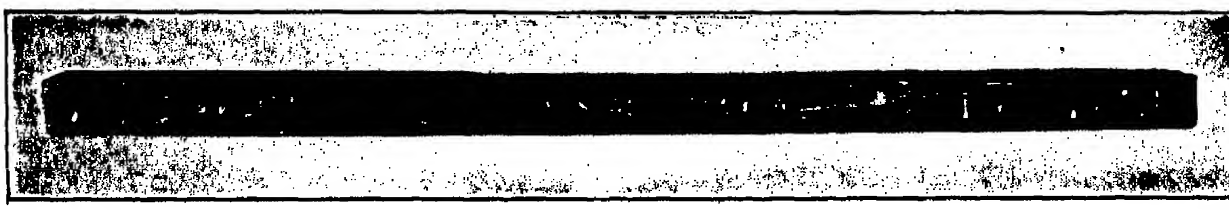


Fig. 3. Tutenkhamon's transit instrument.
Made "with his two hands" for the restoration of the tomb of Thutmose IV. The cartouche of Tutenkhamon appears near the left end.

oldest, in fact, then known to him. It is best described in his own words, taken from a letter written shortly after his return to the United States, while I was still in London:

"I have been very much vexed since I last saw you because at our last meeting I forgot to show you a new and unknown monument of Tutenkhamon which I purchased in London a few days before I sailed. I mention it to you especially because the object turns out to be an astronomical instrument. It is a rectangular strip of ebony wood a little over ten and one-half inches long (perhaps intended for half a cubit), one and one-sixteenth inches wide, thickness just one-half inch. Along each edge, extending entirely from end to end, is an inscription stating that the object was made with his own hands, by King Tutenkhamon as a

restoration of a monument of his father (meaning his ancestor) Thutmose IV. You may remember that the tomb of Thutmose IV contains a remark in ink on the wall reporting that his tomb was restored, of course after robbery, by Harmhab, who was practically the successor of Tutenkhamon. This

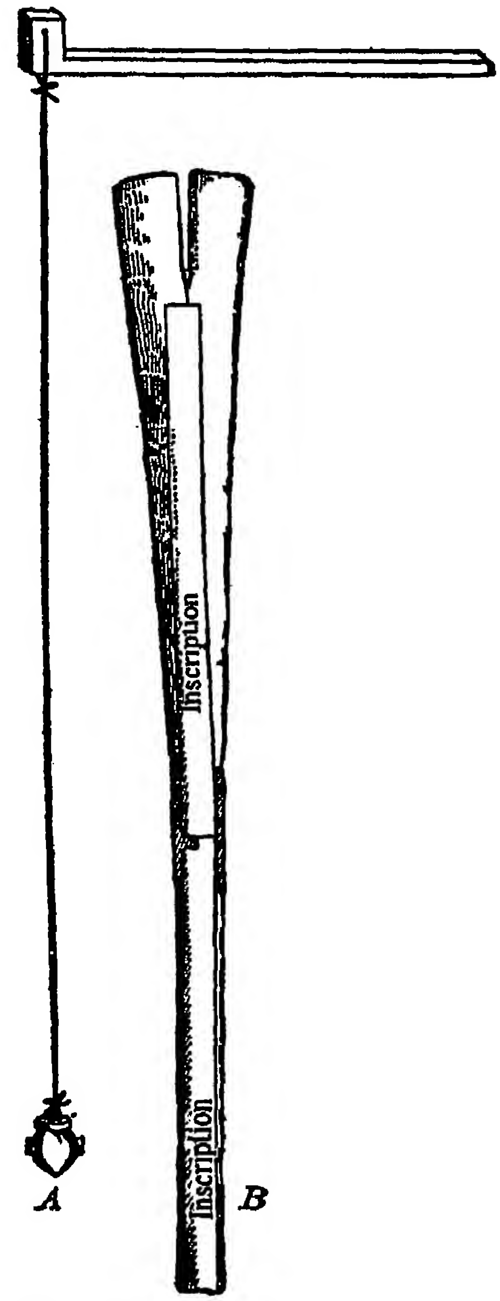
From Breasted, "Ancient Times," by courtesy of Ginn & Co.

Fig. 4. Tutenkhamon's transit instrument.

Note the mortise hole for the end block, and the narrow groove along the inscribed face where the plumb-line fell, as in Fig. 3.

new monument which I am reporting to you can hardly have come from anything else than a tomb in view of the fact that it has escaped destruction for over three thousand years. If so, then the tomb of Thutmose IV had already been robbed under Tutenkhamon's reign, and the latter, whose own tomb was so soon to suffer from tomb-robbers, was endeavoring before the close of his reign to repair their depredations in the tomb of his ancestor Thutmose IV. It is of interest also that the object restored was an astronomical instrument. At one end of the ebony strip is a rectangular mortise hole a little over half an inch long, about three-sixteenths inch wide, and a scant one-fourth inch deep. It is clear that this mortise hole contained a tenon holding in place a little block mounted on the end of

the ebony strip. To the block was attached a plummet, and a vertical line, cut in the edge of the ebony strip exactly opposite the middle of the mortise hole, marks the place where the plummet cord descended. You will find the same instrument somewhat restored in 'Ancient Times,' page 78, Figure 59, marked A. I enclose a little sketch of the ebony strip in which I have restored the little end block from which the plummet was suspended. I do hope when you come through Chicago on your way to California that you will stop in Chicago and see it. My only justification for forgetting to show it to you in London is that I had not, at that time, recognized what the instrument was. It was only after studying the line marking the place of the plummet cord that I recognized the character of the object, the loss of the little block at the end rendering it by no means easy to recognize



From Breasted, "Ancient Times," by courtesy of Ginn & Co.

Fig. 5. Egyptian transit instrument.

The observer looked through the slot in *B*, held close to the eye, and noted the moment when certain stars passed across the plumb-line *A*, suspended in the meridian.

the thing. Its interest lies in the fact that it is the oldest of its kind, far older than the one published by Borchardt, which I have used in 'Ancient Times.'" *

I have since examined this instrument, of capital importance to the history of science, and through Breasted's kindness I am able to give two photographs of it, together with the cut from "Ancient Times" to which he refers. It was known to the Egyptians as the "Merkhet," or "measuring instrument," and is of a type probably used for the orientation of temples as early as 3000 B. C. A complete example described by Borchardt dates from the sixth century B. C., more than seven hundred years later than the reign of Tutenkhamon.

This consists of a sight-vane, made from the middle rib of a palm-leaf, and a plumb-line suspended from an ivory support. One of the hieroglyphic inscriptions on the instrument reads: "I know the path of the sun, moon (?), and stars, each to its place." A meridian line was fixed by an observer sighting north through the slot (held close to the eye) toward the plumb-line, which was held at arm's length and moved east or west until it coincided with a star near the celestial pole. For time determinations two observers, each equipped with a complete instrument, probably sat facing each other on

* A portion of the similar instrument now in the Berlin Museum, more recently published by Borchardt, bears the name of Amenhotep III, and is thus a generation earlier than King Tutenkhamon's transit.

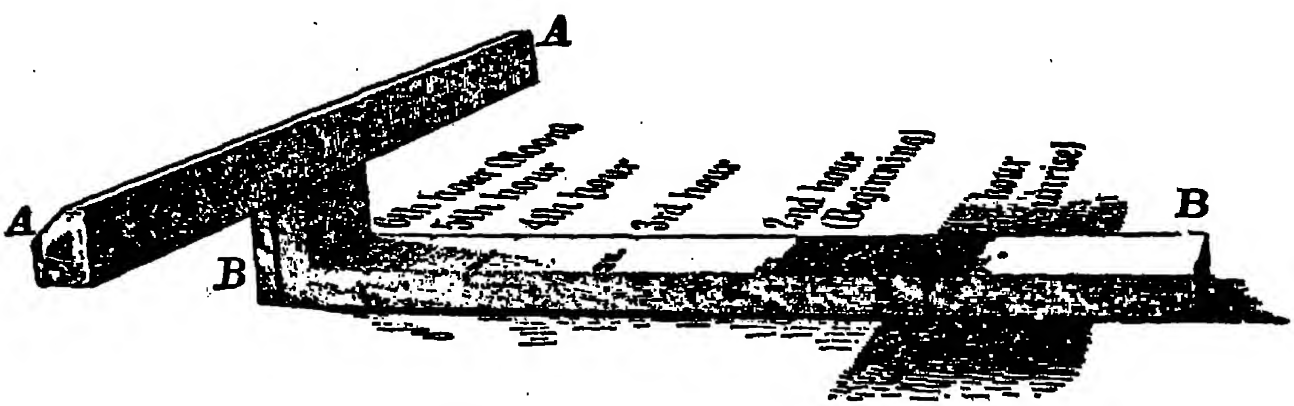
a north and south line. The hours were then defined by the moment at which certain northern and southern stars were seen to cross the vertical cord, aligned on the head, right or left eye, right or left ear, or other feature of the opposite observer. On the 16th of the month Paophi, for example:

1st hour. The leg of the giant, over the heart.
2d hour. The star Petef, over the heart.
3d hour. The star Ary, over the left eye.
4th hour. The claw of the goose, over the left eye.
5th hour. The hinder part, over the heart.
6th hour. The star of thousands, over the left eye.
7th hour. The star of S'ar, over the left eye.
8th hour. The finger point of the constellation of S'ar (Orion), over the left eye.
9th hour. The star of S'ar, over the left elbow.
10th hour. The star that follows Sothis, over the left elbow.
11th hour. The finger point of both stars, over the right elbow.
12th hour. The stars of the water, over the heart.

In Ptolemaic times, as Breasted adds, a picture of this instrument (the part made by Tutenkhamon) was used among the hieroglyphics as a determinative of the word "hour." In earlier times this word always had * after it, showing that diurnal time measurement was a *stellar* matter, doubtless determined by stellar observations. The Greeks called the whole instrument a "horoscope."

It is interesting to speculate whether the sealed boxes in the tomb of Tutenkhamon, of which many

still lie untouched in the inner room adjoining the sarcophagus chamber, will contain one of these instruments. The whole household equipment of the Pharaoh was apparently placed in the tomb, and possibly this may have included a stellar transit. From the inscription already cited it is evident that



From Breasted, "Ancient Times," by courtesy of Ginn & Co.

Fig. 6. Ancient Egyptian sun-clock.

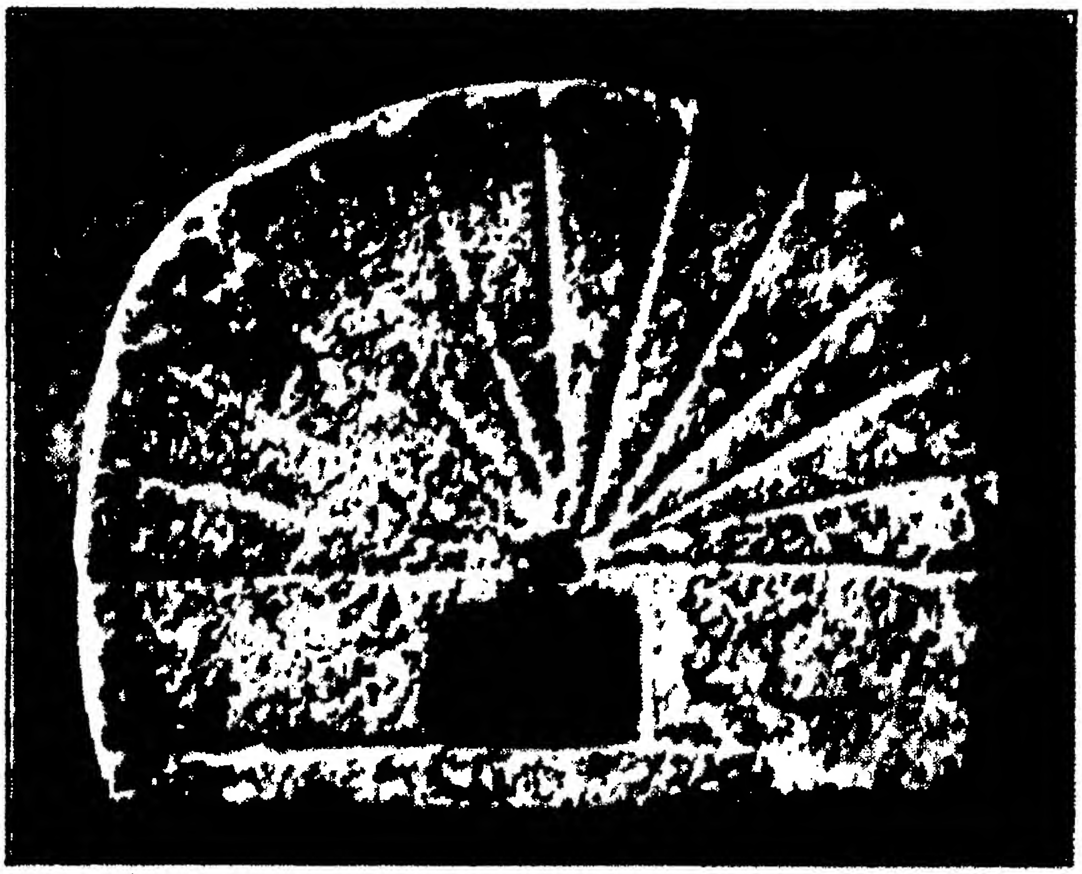
The shadow of the crosspiece (*AA*), turned toward the east in the morning and toward the west after noon, indicated the hour on the arm (*BB*).

Tutenkhamon felt that the tomb of Thutmose IV, after despoilment by robbers, must again be provided with a "Merkhet," doubtless to count the passing of the hours in the nether world. After this mark of filial piety, it is to be hoped that Tutenkhamon's similar needs were not forgotten, and that a complete instrument of this period may yet come to light.

SUN AND WATER CLOCKS

Sun-clocks were also used by the early Egyptians, and one of these, dating from the first half of the fifteenth century B. C., is illustrated in Fig. 6. The

shadow of the crosspiece, which was turned toward the east before noon and then toward the west, indicated the time on the arm *BB*. The interval between sunrise (longest shadow) and noon (no shadow)



From Borchardt, "Altaegyptische Zeitmessung," 1920, by courtesy of the Metropolitan Museum of Art

Fig. 7. Probable Egyptian sun-dial of the period of Mernepthah. Found at Gezer in South Palestine.

was divided into six hours, thus giving ultimately the twelve-hour day to Europe. Several other types of early Egyptian astronomical clocks have been discovered. One found at Gezer in South Palestine, dating from the reign of Mernepthah (about 1200 B. C.), is perhaps the most interesting as the probable prototype of our sun-dial (Fig. 7). An ivory

disk, hung in a vertical plane, carried a projecting bar (gnomon) which cast a shadow on the dial, thus marking the hours in the familiar way.

Water-clocks, later used by the Greeks as the

From Borchardt, "Altägyptische Zeitmessung," 1920, *by courtesy of the Metropolitan Museum of Art.*

Fig. 8. Egyptian water-clock of the period of Amenhotep III (about B. C. 1400).

The water was drained out through a small pipe and the twelve hours of the night were indicated by its level on scales inscribed on the inner face. Found in fragments in the temple of Karnak.

clepsydra, also originated in Egypt. One marked with vertical scales on its inner face, indicating by the falling level of the water the twelve hours of the night (probably between darkness and dawn) for each of the twelve months of the year, was found in

fragments in the temple of Karnak (Fig. 8). It dates from the period of Amenhotep III (about 1400 B. C.), and is made of alabaster decorated in color with constellations and planets, the sun and moon gods, and the king with the gods of the twelve months. The water was drained out through a small pipe, and the form of the vessel was designed to give an equal fall of water in equal times, as a papyrus found in Oxyrhyncus attests. But neither in this form of outflow clock, nor in a better type in which the water dripped into the vessel from another source, was any degree of accuracy attained.

THE GREAT PYRAMID

Much has been written of the Great Pyramid, and many efforts have been made to prove that it was designed to be an astronomical observatory. No competent Egyptologist, however, supports this view. It was carefully oriented, and an open shaft was directed toward the pole of the heavens. But, as Breasted has pointed out, this is easily explained in harmony with its obvious design as the tomb of the Pharaoh. The ancient mortuary texts, inscribed in the chambers of the pyramids, recite that "the King lives among the imperishables." This refers to the belief that he was transmuted into a star, preferably one of the "undying" or "steadfast" stars, so called because they are near the celestial pole and thus never set.

As for the orientation of temples and pyramids, this was an extremely simple process, sufficiently

well accomplished by directing a line toward the rising sun and one toward the setting sun, and bisecting the angle between them. Or the "Merkhet," as already mentioned, may have been employed. Biot, in discussing this subject, expressed his belief that whatever its original purpose, the Great Pyramid subsequently served as an immense gnomon for the determination of the time of the equinoxes, the dates when its east and west faces were grazed by the rays of the rising or setting sun. When still intact, with their perfect masonry and smooth finish, these faces would have served well for this observation, which after a few years of repetition might have measured the solar year to three hundred and sixty-five and one-quarter days, a quantity differing from the true value by about three-quarters of a day in a century. Even in 1853, when the disappearance of the smooth casing stones had already given the Pyramid its present step-like contour, Mariette, following Biot's instructions, thus determined the time of the vernal equinox within about twenty-nine hours. At that period the inhabitants of the neighboring villages knew that the rays of the setting sun at the equinox grazed the faces of the Pyramid, and the Sheik of Koneisseh told Mariette that the extremity of the shadow, which was about three kilometres long a quarter of an hour before sunset, fell near a granite rock a little north of this village.

The early establishment of the Sothic year, the orientation of pyramids and temples, and the invention and long-continued use of simple instruments,

which were ultimately incorporated among the hieroglyphic characters and are also depicted in larger scale on the walls of temples and tombs, bear out the tales of early Greek travellers regarding the origin of astronomical observation in Egypt. But the apparent inability of the Egyptians to advance beyond their promising beginnings, and their failure to attack any of the real problems of astronomy, compel us to look elsewhere for the true foundations of astronomical research. In spite of a great admixture of superstition and magic, we find evidence of marked progress when we pass from the valley of the Nilė to the banks of the Euphrates.

SORCERY AND SCIENCE IN CHALDEA

Fortunately for our knowledge of ancient astronomy, the cuneiform tablets of the Babylonians and Assyrians, far less fragile than the papyri of the Egyptians, have survived to our day in great numbers. When the royal library at Nineveh was enlarged by Assurbanipal, King of Assyria from 668 to 626 B. C., the added tablets included many relating to the astrology of the ancient Babylonians and the still more ancient Sumerian invaders. One series, known as "The Day of Bel," was ascribed by the wise men of the time to the period of the great Sargon I, about 2800 B. C. Guided by these antique documents, the soothsayers of the last Assyrian Empire reported periodically on both celestial and terrestrial happenings and predicted future events. High in rank and hereditary in office, the chief as-

trologer and many other functionaries whose names have come down to us frequently addressed the king from all parts of the empire. The tablets contain astronomical reports and astrological deductions based upon them. If the moon's horns were observed to be pointed, "the king will overcome whatever he goreth." The moon was also supposed to influence sheep and cattle, and lunar as well as solar halos were eagerly watched as a means for prediction, especially of rain. Omens were also based on the entrance of the planets into the signs of the zodiac, while eclipses, as sources of disturbance, called for supplications to the protecting gods.

Although the Assyrians and Babylonians were so famed for astrology and magic that the very name "Chaldean" became synonymous with sorcerer, it remains true that they contributed notably to the establishment of astronomy as a science. Passages in their astrological tablets indicate that the calculation of times and seasons was a prime duty, and there is some evidence that they possessed instruments for measuring time. The term *abkallu sikla* on one of the astrological tablets is translated "measure-governor" by Thompson, who believes it to represent some kind of clock. From the early appearance of the water-clock in Egypt, and the attribution of the clepsydra or some other form of time-measurer to the Chaldeans by Sextus Empiricus and Herodotus, there is little doubt of the correctness of this conclusion. Their tablets also mention a time unit, called *kasbu*, equal to two hours. A

watch consisted of two *kasbu*, and three watches completed the night. The Assyrian year contained twelve lunar months, usually of thirty days each, with an intercalary month added from time to time. Even during the earliest period the tablets contain

From a drawing by Felix Thomas, "Expédition Scientifique de Mésopotamie."

Fig. 9. The ruins of Birs-Nimroud.

The ancient Chaldeans made their astronomical observations from the summits of such towers.

many lists of stars, observations of the moon, eclipses, planets, comets, altitudes of the sun and moon, etc. After the seventh century B. C. the interests of astronomy were more clearly recognized and no indications of the art of the diviner are found in a large body of tablets of this period.

OBSERVATIONS AND PREDICTIONS

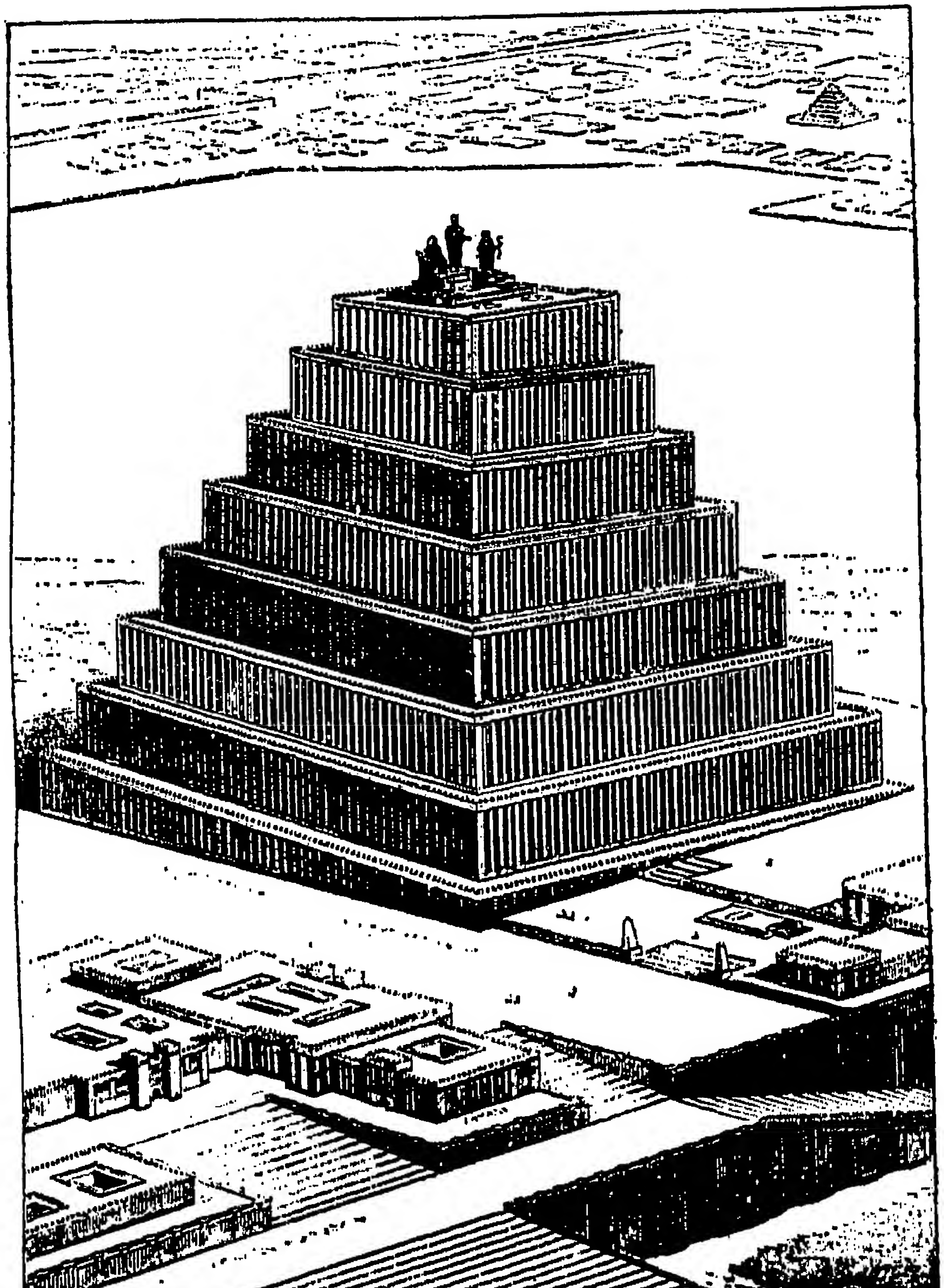
These tablets are of two classes, one containing observations, the other computations. The obser-

vational tablets include the positions of the sun, moon, and especially the planets, the latter given with reference to neighboring stars. At first a star was designated as indicating the place of a planet in its vicinity. But during the last four centuries B. C. angular measurements of position were made, though nothing is yet known as to the nature of the instruments employed. A high degree of precision was attained in the determination of the period of revolution of the planets, and eclipses of the sun and moon were successfully predicted.

One of the oldest computational tablets yet discovered is in reality a page from an astronomical ephemeris computed for the year 425 B. C., the fortieth year of Artaxerxes I. The left-hand column, both on the obverse and reverse sides, contains for each month the length of the month, the date of full moon, and the date of the moon's last visibility. The right-hand column predicts the dates of the heliacal rising and setting of planets and stars. On the reverse two additional predictions are included, as follows:

On the first Mercury rises.
On the third the Equinox.
Night of the 15th, 40 minutes after sunset an eclipse of the moon begins.
On the 28th occurs an eclipse of the sun.

Kugler, who translated the tablet, calculated that these eclipses actually took place on October 9 and 23, in 425 B. C. The eclipse of the moon was vis-



From Perrot and Chipiez, "Histoire de l'Art dans l'Antiquité," by courtesy of Librairie Hachette, Paris.

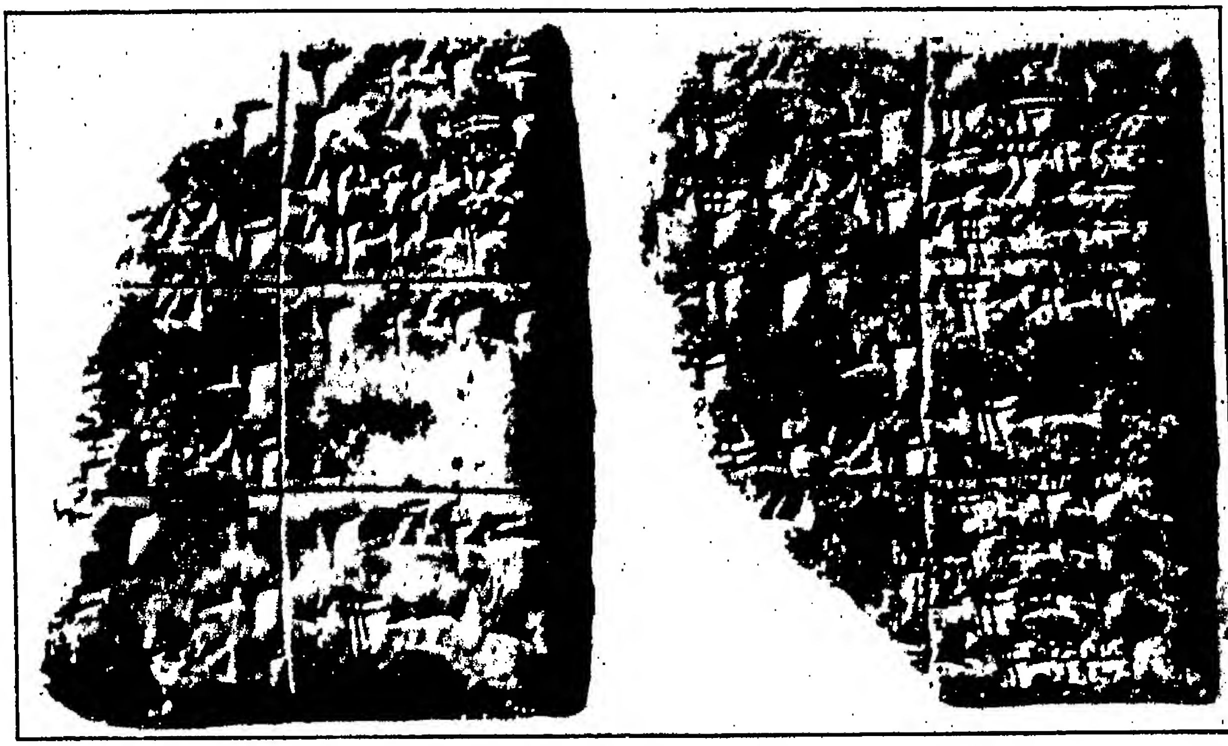
Fig. 10. Restoration by Chipiez of the Temple Tower of Khorsabad.

This tower, now in ruins, has been called "the observatory" because of its use by the Chaldean astronomers.

ible in Babylon, but that of the sun could be seen only at some distance from the city.

These predictions of the Babylonian astronomers were undoubtedly based on their discovery of the Saros, the eclipse cycle of eighteen years and eleven days, or two hundred and twenty-three lunations, after which the same succession of eclipses recurs, though not at the same places. It was from Babylonian sources that travellers like Herodotus derived the elements of the astronomy which the Greeks rapidly developed into an exact science. In fact, a Babylonian quoted by Strabo as Kidĕnas and by Pliny as Cidenas has been identified as the author of a cuneiform tablet of moon data signed by the astronomer Kidinnu. It cannot be said, in spite of the value of their observations, that the Babylonians made any original contributions to the instruments of the astronomer. The gnomon and the sun-dial, attributed to them by Herodotus, were used centuries earlier by the Egyptians, and the water-clock, as we have seen, was also of Egyptian origin. Nevertheless, the long practice of astronomy by the Babylonians, the care and accuracy of their observations, and the imposing towers used as their observatories, profoundly influenced the Greeks. The ruins of the temple of Bel, from whose summit the astronomer priests observed the heavens for centuries, must have deeply impressed the scholars who accompanied Alexander the Great on his campaign in India and the Near East. As Draper remarks, the stimulus of the discoveries made by this expedition, among the

widest variety of geological formations and paleontological remains and the strange and varied fauna and flora between the cataracts of the Nile and the banks of the Indus, aided in preparing the way for



From Breasted's "The Origins of Civilization," by courtesy of the Scientific Monthly.

Fig. 11. Babylonian tablet inscribed with astronomical ephemeris for the year B. C. 425.

The left-hand column, both on the obverse and reverse sides, contains for each month the length of the month, date of full moon, and date of the moon's last visibility. The right-hand column predicts the dates of the heliacal rising and setting of stars and planets.

the remarkable researches of the Greeks, the true founders of modern science.

THE RISE OF ASTRONOMY AMONG THE GREEKS

Homer and other ancient poets had conceived the earth to be a plane surface, encircled by the ocean,

where the heavenly bodies rise and set and the burning sun hisses as he plunges beneath the waves. The Ethiopians, living near the margin of the earth, were therefore supposed to be scorched by the sun's close approach. This fabulous age was soon succeeded by the most striking developments, due to the extraordinary powers of the early Greek mathematicians and astronomers, who derived stimulating suggestions, primitive instruments, and important observational data from Egypt and Babylonia. Thales (about 600 B. C.), who learned in Egypt the empirical geometry of the priests, rapidly developed abstract geometry, and mathematics was raised to a science by Pythagoras, Apollonius, Euclid, and other members of the Alexandrian School. At the same time astronomy made equally striking advances.

The apparent annual motion of the sun among the stars is the basis of astronomy, and the knowledge of the sun's path gained by the Egyptians and Babylonians was brought to Greece at a very early period. The obliquity of the ecliptic, or inclination of the sun's path to the celestial equator, was measured by Meton in the year 430 B. C. Doubtless he employed a gnomon, the simplest of the astronomical instruments handed down by the Egyptians and Babylonians. It consists merely of a vertical pillar, whose shadow gives the direction and altitude of the sun. The lengths of the longest and shortest shadows, cast by the gnomon at noon at the time of the winter and summer solstices, afford the means of determining the obliquity of the ecliptic. An-

other very early instrument is the hemispherical sun-dial, in which the position of the shadow of a point at the centre of a hollow hemisphere was read on the concave surface marked with circles. A huge

From Kaye, "The Astronomical Observatories of Jai Singh," by courtesy of the Superintendent of Government Printing, Calcutta, India.

Fig. 12. The Jai Prakas or "Crest Jewel of all Instruments" of the Observatory at Delhi.

A huge existing example of the hemispherical sun-dial of the Greeks.

existing example of this is the "Jai Prakas" of the Hindu Maharajah Jai Singh (Fig. 12).

Practical and religious needs and the art of divination largely controlled the astronomy of the Egyptians and Chaldeans. The Greeks, on the contrary, show from their beginnings an entirely different attitude, sometimes weakened by mysticism, but in most cases identical with that of the modern in-

vestigator. Nearly four centuries before the Christian era Eudoxus developed a geocentric theory of the solar system and endeavored to test it by observation. Aristarchus of Samos (310–250 B. C.) held, in early anticipation of Copernicus, that the apparent motions of the sun, moon, and stars are due to the rotation of the earth on its axis and its revolution around the sun. Aristotle objected that in this case the stars should appear to shift in position when viewed from opposite ends of the earth's orbit. Aristarchus, in spite of the prevailing opinions of his time, replied that they were too far away to show any sensible change in direction. He was right, but the lack of instruments capable of detecting their excessively small parallax, or annual displacement, caused by the earth's motion, made possible the dominance of the geocentric doctrine set forth by Ptolemy in the Almagest, an astronomical classic that controlled human thought for fifteen centuries.

PTOLEMY'S ALMAGEST

This truly remarkable book, which embodies the results of Hipparchus and other astronomers who preceded Ptolemy, reveals both the strength and the weakness of Greek science. Following Aristotle, Eratosthenes, and others, Ptolemy clearly demonstrated the sphericity of the earth, which he fixed at the centre of the concave sphere of the heavens. He ridiculed those who believed in the earth's orbital motion and axial rotation, and proved to his

own satisfaction that the sun, planets, and stars revolve about it. The changing distances of the sun and moon, shown by their variation in apparent diameter, had been attributed by Hipparchus to a displacement of the earth from the centre of the circles in which they were supposed to move. To account for the backward and forward motions of the planets, which actually result from the modification of their steady orbital motion by the revolution of the earth about the sun, Hipparchus invented the system of epicycles, in which each planet is supposed to rotate in a small circle about a centre which moves at uniform speed in a large circle around the earth. These artifices sufficed to represent the motions of the sun, moon, and planets as then roughly known, and through the support of the Church and the wide-spread use of the Almagest, the Ptolemaic theory held sway until the reasoning of Copernicus (1473–1543), the improved observations of Tycho Brahe (1546–1610), the formulation of the laws of planetary motion by Kepler (1571–1630), and the discoveries of Galileo (1564–1642) finally led to its downfall.

The star catalogue in the Almagest remained until the time of Tycho Brahe the only widely available list of the positions and brightness of stars. The observations on which it is based were actually made by Hipparchus of Rhodes (about 130 B. C.), the greatest astronomer of antiquity. Fortunately, Ptolemy preserves for us a description of the instruments used by Hipparchus and other early Greek

astronomers. In principle, most of these consist essentially of a graduated arc of a circle, ranging from a sextant to an entire circumference, supported in the plane in which the measure is to be made.

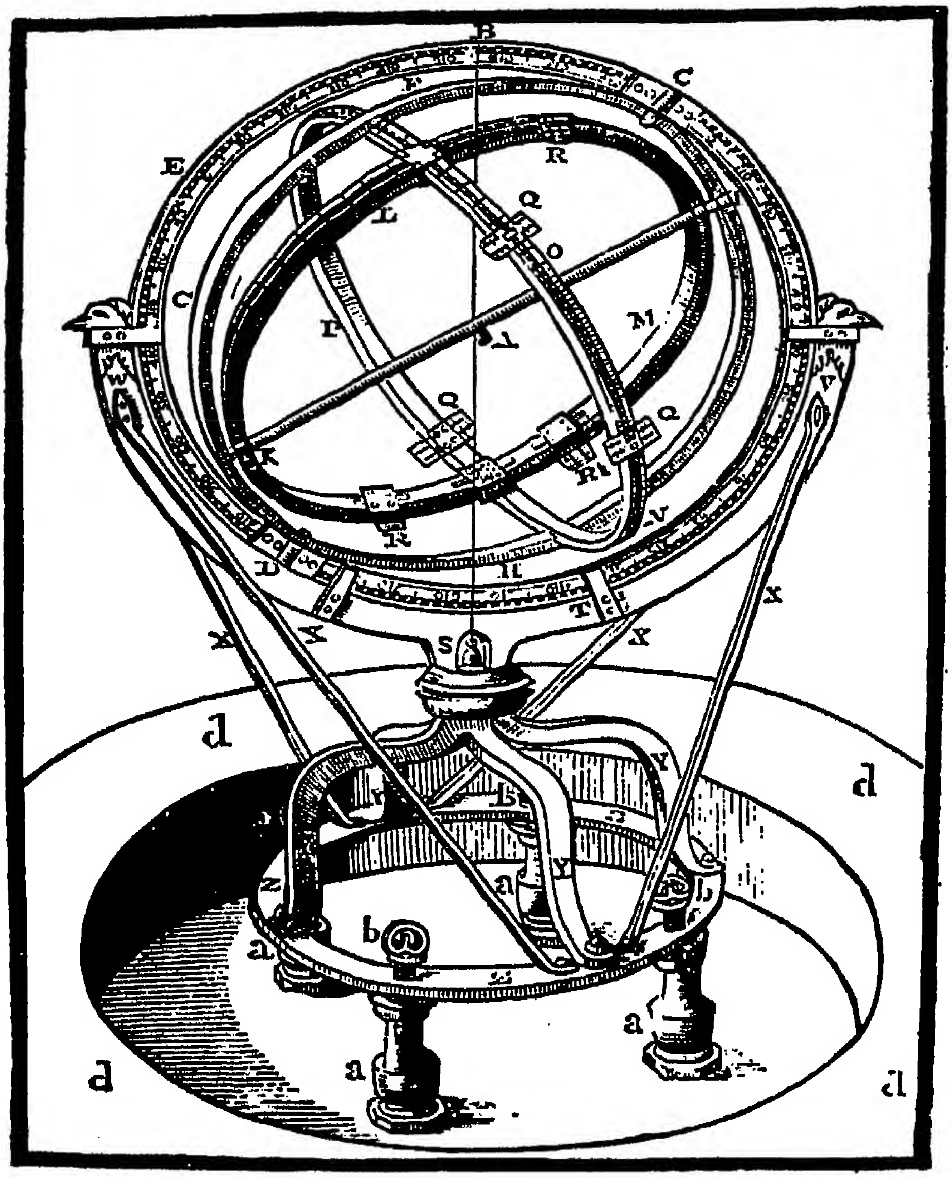
THE INSTRUMENTS OF THE GREEKS

The simplest of these instruments, used for observing the altitude of the sun at the solstices, and thus for determining the obliquity of the ecliptic and the length of the year, probably goes back to the time of Timocharis and Aristillus, whose observations were made in the great Museum of Alexandria about 300 B. C. It consisted merely of a copper ring, graduated with degrees and subdivisions, and mounted vertically in the meridian. Within it a second ring rotated in the same plane. This carried two diametrically opposite pins, with pointers for reading the circle. The altitude of the sun at noon was measured by turning the inner ring until the shadow of the upper pin fell centrally on the lower one.

The zodiacal armilla, which dates from Hipparchus or his predecessors, was used to measure the positions of the stars. It comprised a large circle rigidly fixed in the meridian, with a slightly smaller circle turning within it on pivots corresponding to the north and south poles of the heavens. This inner circle carried pivots corresponding to the poles of the ecliptic, with circles and adjustable sights permitting observations of stellar latitudes (above or

below the ecliptic) and longitudes (east or west along the ecliptic).

The mural quadrant, developed later by the Arabs

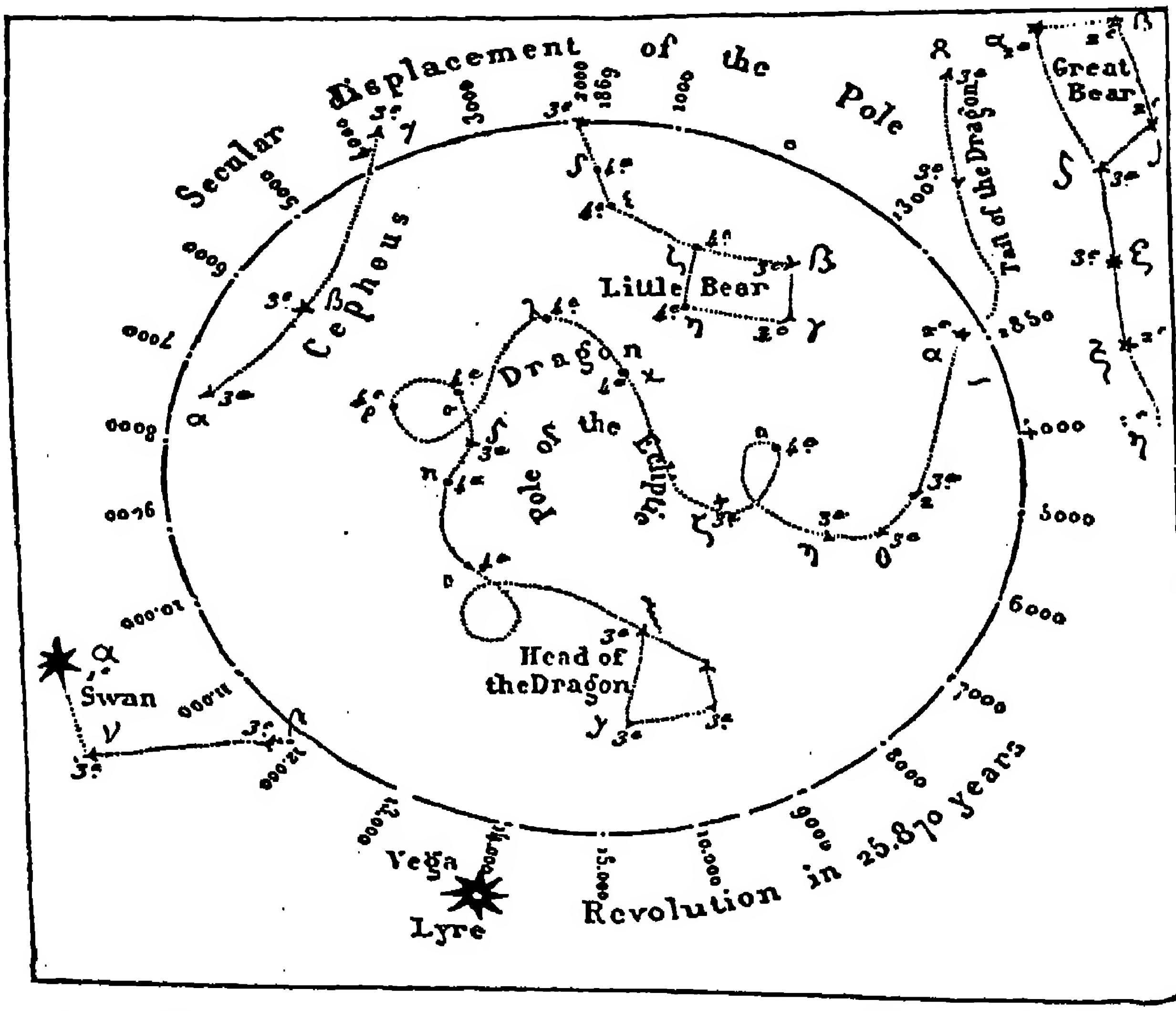


From "Stargazing," by Lockyer, by permission of Macmillan and Company.

Fig. 13. The Zodiacal Armilla of Tycho Brahe, similar to the ancient instrument of Hipparchus.

and by Tycho Brahe, is described in a small form by Ptolemy in the Almagest. When measuring the altitude of the sun the shadow of a pin at its centre

was observed on the divided arc of a quadrant, attached to a cube of stone or wood and set in the meridian. For the planets and stars sights were



From "Stargazing," by Lockyer, by permission of Macmillan and Company.

Fig. 14. Revolution of the pole of the equator about the pole of the ecliptic caused by the precession of the equinoxes.

used, as in Tycho Brahe's large instrument (Fig. 13). Mention should also be made of the diopter of Hipparchus, used to measure the angular diameter of

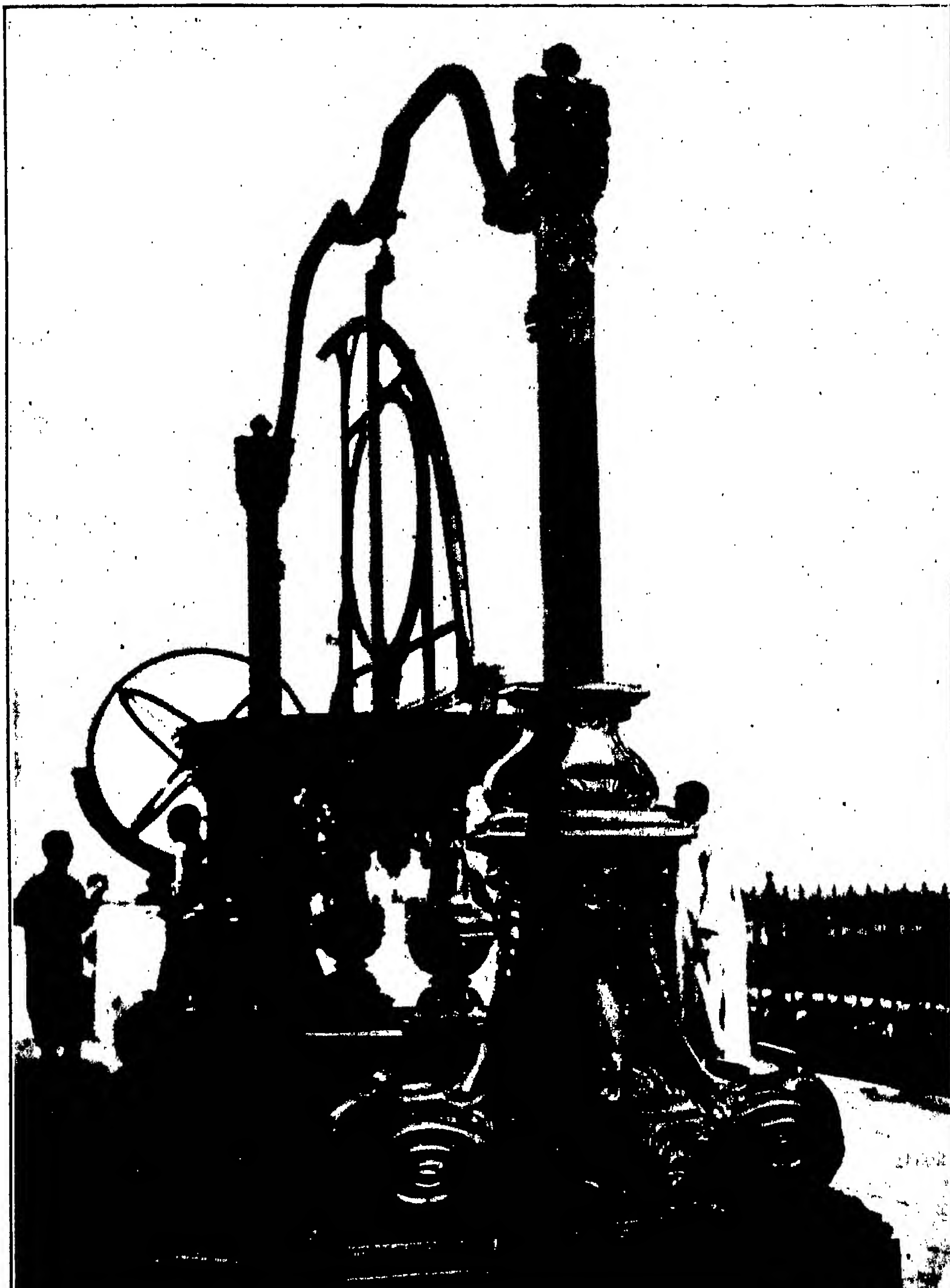


Fig. 15. Astronomical instruments on the walls of Pekin.

the sun or moon. A pin sliding along a rod was moved until it exactly covered the solar or lunar disk, seen through a sight at the lower end of the rod.

Astronomy thus became a science in Greek hands and was placed on a firm foundation through their development of geometry and trigonometry, their invention of well-designed instruments, and their measurement and remeasurement of celestial objects as a test of carefully formulated theories of the solar system. The precession of the equinoxes, due to the revolution in about twenty-six thousand years of the axis of the earth (the pole of the heavens) about the pole of the ecliptic, detected by Hipparchus by comparing his position of the bright star Spica with that determined by Timocharis and Aristillus a century and a half earlier, was the greatest discovery of antiquity. Physics, later destined to transform astronomy through the advances of Galileo, Newton, and their successors, was also firmly established by Archimedes and other members of the Alexandrian School. With such beginnings, science should have advanced rapidly. But Alexandria, the first great centre of research, declined. Mathematical and experimental science gave place to mysticism and magic. Greece was succeeded by Rome, and research was abandoned under the trammels of tradition and authority. Fortunately, though science vanished from Alexandria and was repressed in Europe, it was kept alive by the Arabs, who devoted special attention to astronomy.

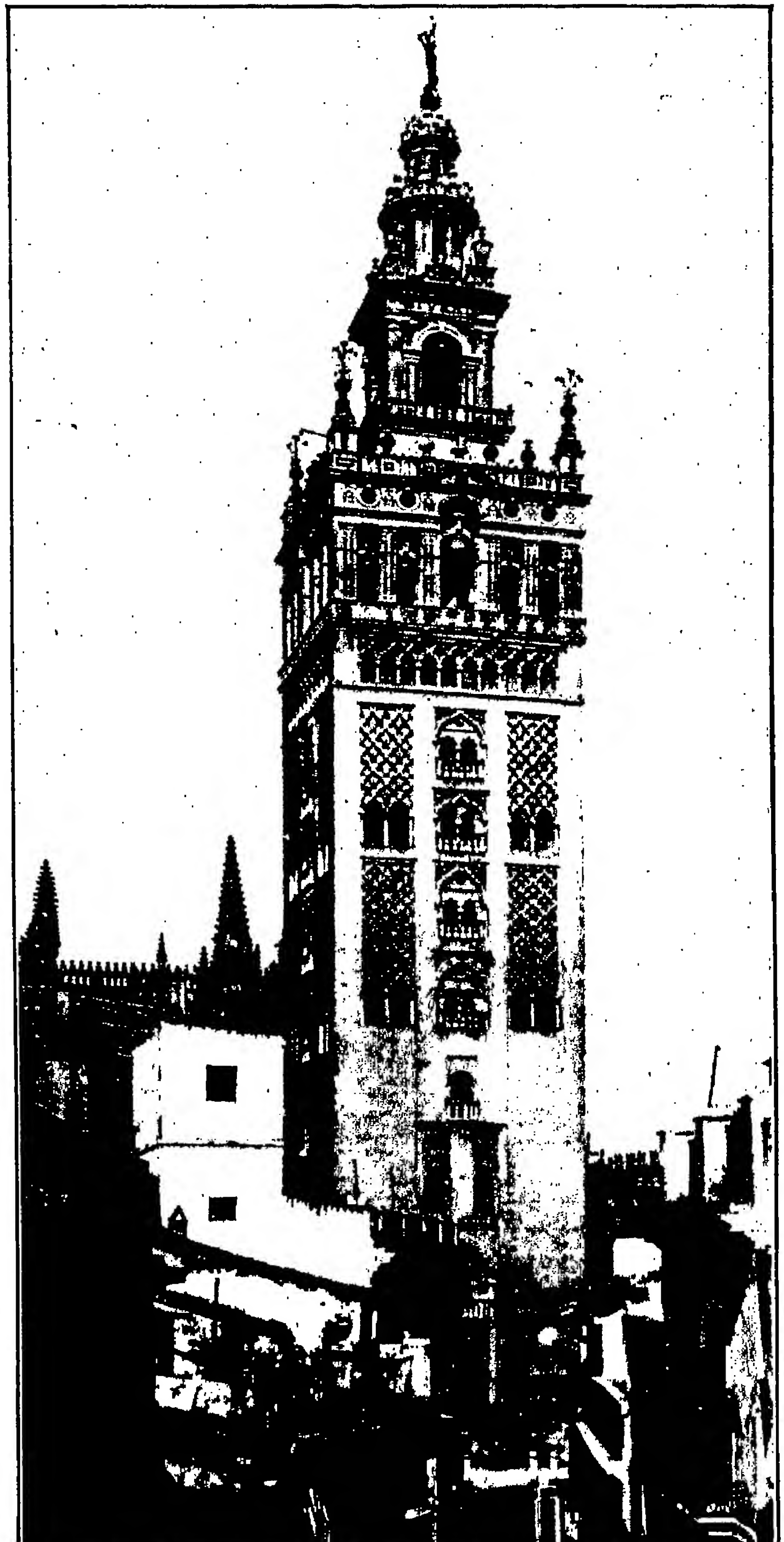


Fig. 16. The Giralda, Seville.

Erected by Yakub-al-Mansur in the twelfth century and used by the Moors as an astronomical observatory.

THE CHINESE AND HINDUS

The ancient Chinese and the Hindus, though their observations go back to very early times, contributed little or nothing to the observational methods of the astronomer, and their instruments appear to follow Greek models. The attitude of the Hindu astronomers toward exact measurements is summed up in a remark in the Siddhanta Siromani by Bhaskara, one of their number: "But what does a man of genius want with instruments, about which numerous works have treated? Let him only take a staff in his hand and look at any object along it, casting his eye from its end to the top. There is nothing of which he will not then tell its altitude, dimensions, etc." In striking contrast is the practice of the great Maharajah Jai Singh of Jaipur (1686 1743 A. D.), whose five observatories are still among the most remarkable sights of India. Although a Hindu, he studied Moslem and European methods impartially, and his enormous instruments are copies or developments of those of Ulugh Bey, of Greek and Moslem origin. The celebrated Chinese instruments on the walls of Pekin were also built on Greek models.

THE MOSLEM PERIOD

A striking chapter in the history of science is that of the Moslem period, following in the wake of their conquests from Arabia eastward to Persia and westward through Egypt and the whole north African

Fig. 17. Old Persian astrolabe, presented to the author by the late Sir James Dewar.

Chaucer recommends that the astrolabe be used as follows: "Put the ring of thyn Astrolabie up-on thy right thoumbe and turne thy left syde agayn the light of the sonne. And remeve thy rewle up and doun, till that the stremes of the sonne shyne thorgh bothe holes of thy rewle. Loke thanne

coast into Spain. Their careful measurements of the sun, moon, planets, and stars led to important advances, and we are also indebted to them for their contributions to the development of algebra and trigonometry. Best of all, they kept science alive, and maintained a high level of civilization while most of Europe was at the lowest ebb. The Almagest was their great work of reference, and their instruments were modelled after those of the Greeks. In their hands the astrolabe, of antiquity so great that Gallucci (1595) repeats the tradition that it was made by Adam for the instruction of his children, was so universally and persistently employed that it can still be purchased in the bazaars of India, where it is in common use by the astrologers. It consists of a graduated circle on which a revolving diametral arm, furnished with pinnules or sights at its extremities, is pointed at the celestial object (Fig. 17).* Its obvious limitations when supported by the hand led to the provision by the Greeks of more stable mountings and a progressive increase in the size of the circle, illustrated by the great astrolabes of Jai Singh. A Moslem writer, Ibn Carfa, remarked that if he could do so, he would construct a circle supported on one side by the Great Pyramid and on the other by the Mokattam Hills, eight miles away across the Nile!

* Chaucer's "The Conclucions of the Astrolabie" quaintly sets forth the many uses of this instrument, for the benefit of his son.

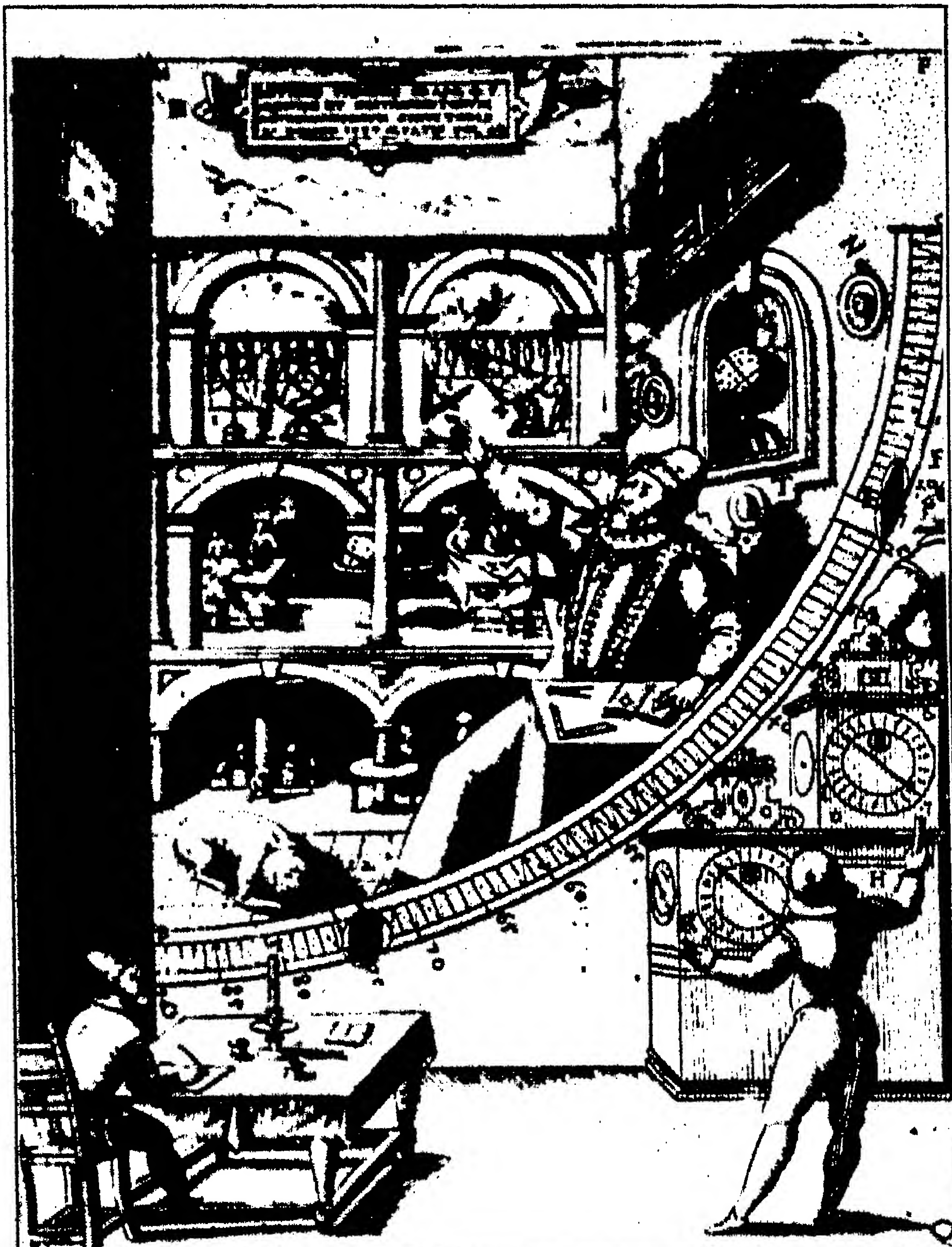
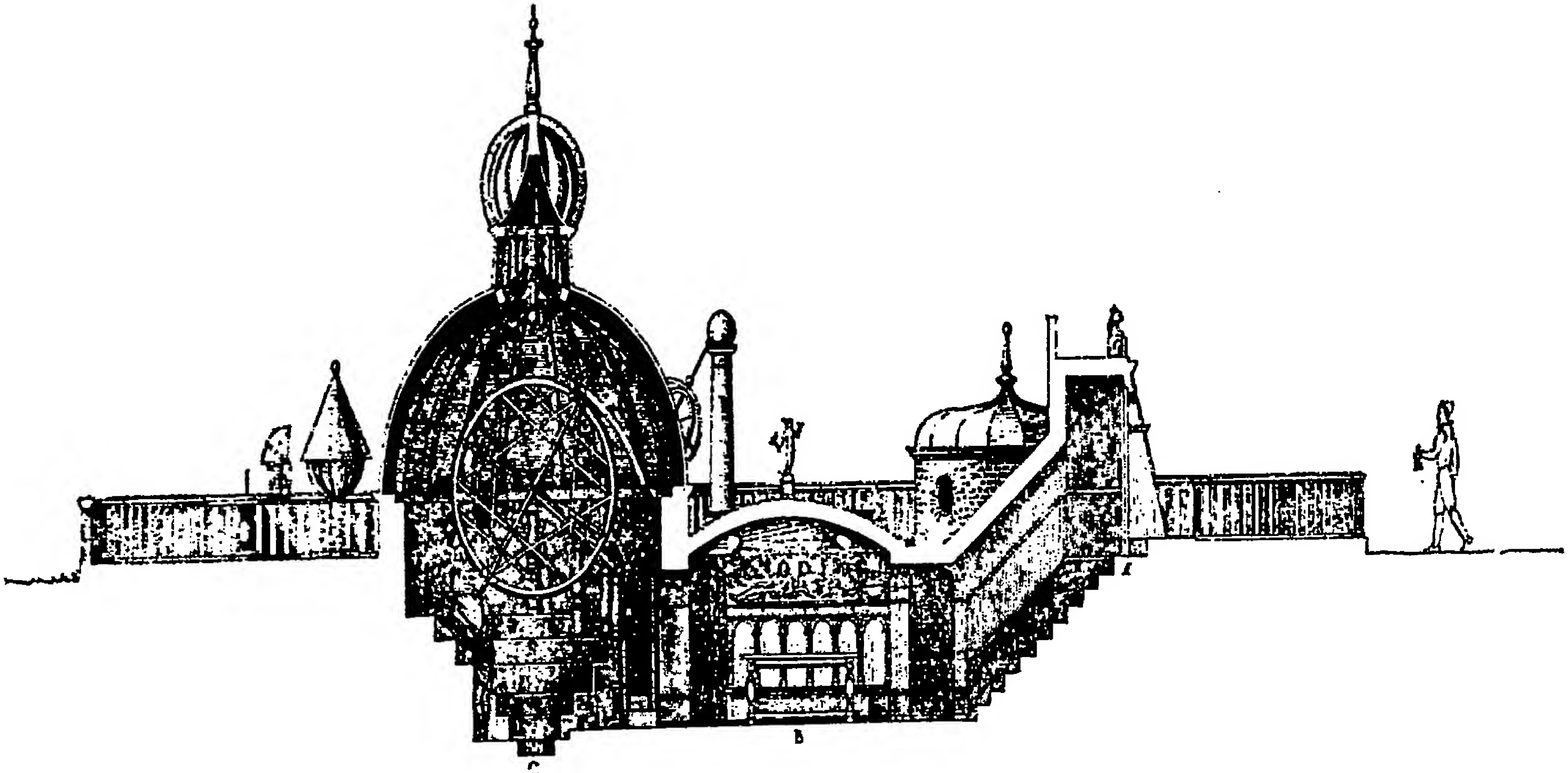


Fig. 18. Tycho Brahe's great mural quadrant.

The astronomer at the extreme right is observing a star through the sights. Above the arc of the quadrant is a painting of Tycho and some of the instruments of his observatory.

TYCHO BRAHE

Perhaps the most striking tribute to the skill of their early designers is afforded by the fact that practically all of the instruments of the Danish astronomer Tycho Brahe, the last great observer prior to the invention of the telescope, are of Greek model. He devoted himself to their improvement, and the elaborate equipment built in his own shops for the great Observatory of Uranibourg embodies valuable advances, such as his method of transversals for subdividing the graduations of circles. Thanks to these, and to his skill and assiduity as an observer, the greatly increased precision of his star places enabled Kepler to discover his celebrated laws of planetary motion. But like all his predecessors, he was still confined by the limitations of the naked eye, and he could see no farther into the depths of space than the earliest star-gazers of paleolithic times. A radical advance, embodying a new but simple principle, was needed, and this he missed, though it lay within his very grasp. Spectacles had been known for three centuries, and may have been worn by members of his observatory staff. But neither the lucky chance in combining two lenses that first revealed the powers of the telescope, nor the knowledge of optics that enabled Galileo instantly to design his own instrument, came to Tycho's aid. Surrounded by the perfected instruments of the Alexandrian School, which he used so long and so effectively, he stands as the last great observer before the dawn of the telescopic age.



From Christensen and Beckett, "Tycho Brahe's Uraniborg and Stjerneborg on the Island of Hveen," Oxford University Press, London, 1921.

Fig. 19. Section through Tycho Brahe's subterranean observatory "Stjerneborg," showing his equatorial armilla, with declination circle 9½ feet in diameter.

HEAT FROM THE STARS

Light is the most universal of all languages. Its messages reach us with equal facility from the depths of the universe and from the electrons whirling in the nearest atom. Like the hieroglyphics of the Egyptians, its tones are silent, but, unlike them, it tells of the present as well as of the past. Its daily reports from the most distant stars were despatched millions of years ago, but within the limits of the solar system its slowest deliveries are completed within a few minutes, and on earth within small fractions of a second. The new knowledge that it brings is of the most varied character, ranging from the constitution of matter to the structure of the universe. Recently it has told us much of the evolution of the stars, whose life-cycles we are at last beginning to comprehend.

A few years ago Russell advanced his now famous theory of giant and dwarf stars. Starting from the early conceptions of Lane and Ritter, but developing them in the light of modern discoveries, he sketched for us the extraordinary characteristics of early stellar life. Nebulæ we had previously pictured as vast regions of space filled with faintly glowing rarefied gases, and stars were supposed to condense out of them. No one imagined, however,

that a fully formed star like Betelgeuse, which marks the right shoulder of Orion, could actually be a gaseous sphere some 300,000,000 miles in diameter, so highly rarefied that its average density is far less than that of the air we breathe. To test this theory and to prove beyond doubt the tremendous rise in temperature and decrease in diameter which it indicated for the successive stages of stellar life has taxed the capacities of our ablest astronomers and best-equipped observatories. Fortunately, we are in the midst of a period of rapid progress, in which new instruments and methods are keeping pace with the demands of new theories. Some of these have been described in previous volumes.* But other vital steps remained to be taken, one of which was to measure with precision the radiant energy of the stars, and especially to determine the relative proportions of the visible and invisible rays emitted by the cooler ones.

VARIETIES OF RADIATION

It was in 1666 that Newton made the first analysis of sunlight with a prism. After him more than a century elapsed before Sir William Herschel took the next step. Fig. 20, from Herschel's paper in the "Philosophical Transactions of the Royal Society" for 1800, shows the simple but effective means employed by him to supplement the limited powers of the eye. The spectrum of sunlight, formed by a

* "The New Heavens" and "The Depths of the Universe," Charles Scribner's Sons.

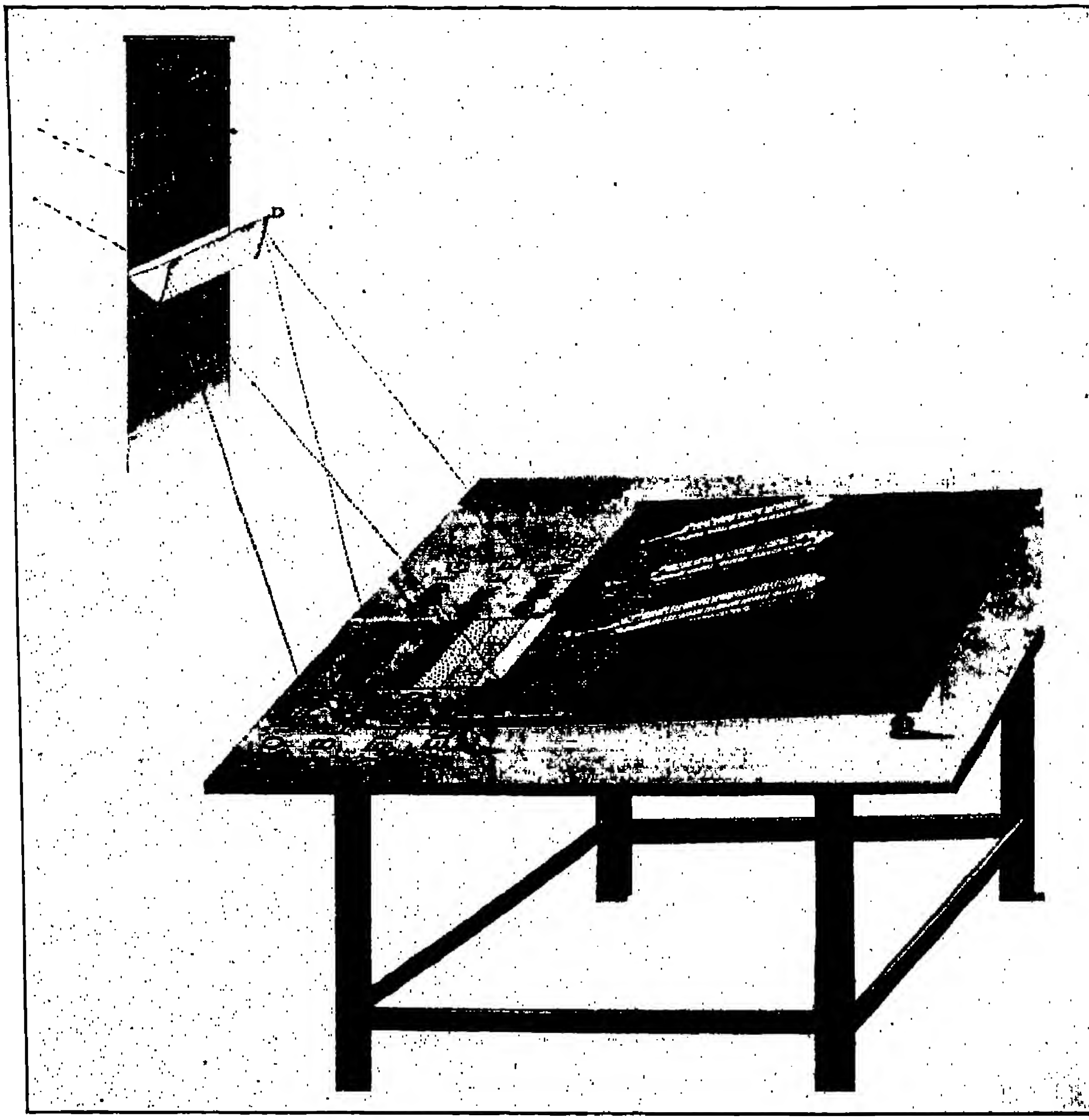


Fig. 20. Herschel's discovery of the invisible infra-red rays.
The infra-red portion of the solar spectrum, which cannot be seen by the eye, was detected by means of its heating effect on thermometers set at various points beyond the red end of the visible spectrum.

prism on the white surface of a table, was visible through the well-known range from violet to red. But at these limits it seemed to stop. A thermometer, exposed to the violet, showed a slight heating

effect, but no sign of radiation was found beyond these visible rays. At successive points toward the red the thermometer rose higher and higher, but at this end of the visible spectrum the heating effect did not cease. On the contrary, the exposed thermometer continued to give higher readings after it had been moved entirely beyond the range of the red. In other words, the maximum heating effect of the sun's rays when analyzed by a prism seemed to lie in an invisible region beyond the red, since known as the infra-red. Herschel rightly concluded that light and radiant heat are identical, their observed effects simply depending upon the powers of the receiving instrument. The human eye responds only to the rays from red to violet, while his thermometer detected not only these rays but also others, which are less refracted by the prism. Later he gave further evidence of this identity, by proving that the invisible heat rays can be reflected and also refracted by concave mirrors or lenses, in the same way as light rays. We are all familiar with such invisible heat rays, which are given by a stove long before it is heated to redness.

This first step into the invisible having been taken, within a year Ritter discovered the existence of ultra-violet rays, beyond the visible violet, by their effect in blackening silver chloride. Then followed, in 1802, the great advance of Thomas Young—the first measurement of the wave-lengths of light of various colors. He found that the difference between red and violet is merely a difference in wave-

length, the waves of the former being about half again as long as those of the latter. A simple experiment will make this difference clear.

Take a long piece of rope and fasten one end to a post. Hold the other end in the hand, with the rope drawn nearly taut, and vibrate it up and down. It is easy to make waves run along the rope from the hand to the post. If the hand is moved quickly, the waves will be short. If more slowly, the waves will be longer. In the case of violet light the vibration frequency is high and the waves are very short. For yellow light the frequency is lower and the wave-length greater (about $\frac{1}{50000}$ inch). Toward the red and in the infra-red the wave-length continues to increase, as Fig. 21 illustrates. The extent of the spectrum has grown with the development of new and more sensitive instruments and the discovery of radiations, such as the X-rays, which were at first supposed to be utterly unlike the rays of light. Now we recognize no distinction, except that of wave-length and the diverse effect on our receiving instruments, as we pass from the shortest known radiations recently studied by Millikan (see page   ) through the ultra-violet into the visible spectrum, and then beyond its red end into the immense range of increasing wave-lengths which finally culminates in the longest radio waves.

The illustration (Fig. 21) is due to the late Ernest Fox Nichols, who presented it in connection with a paper read before the National Academy of Sciences as the last act of his life. Just as he concluded its

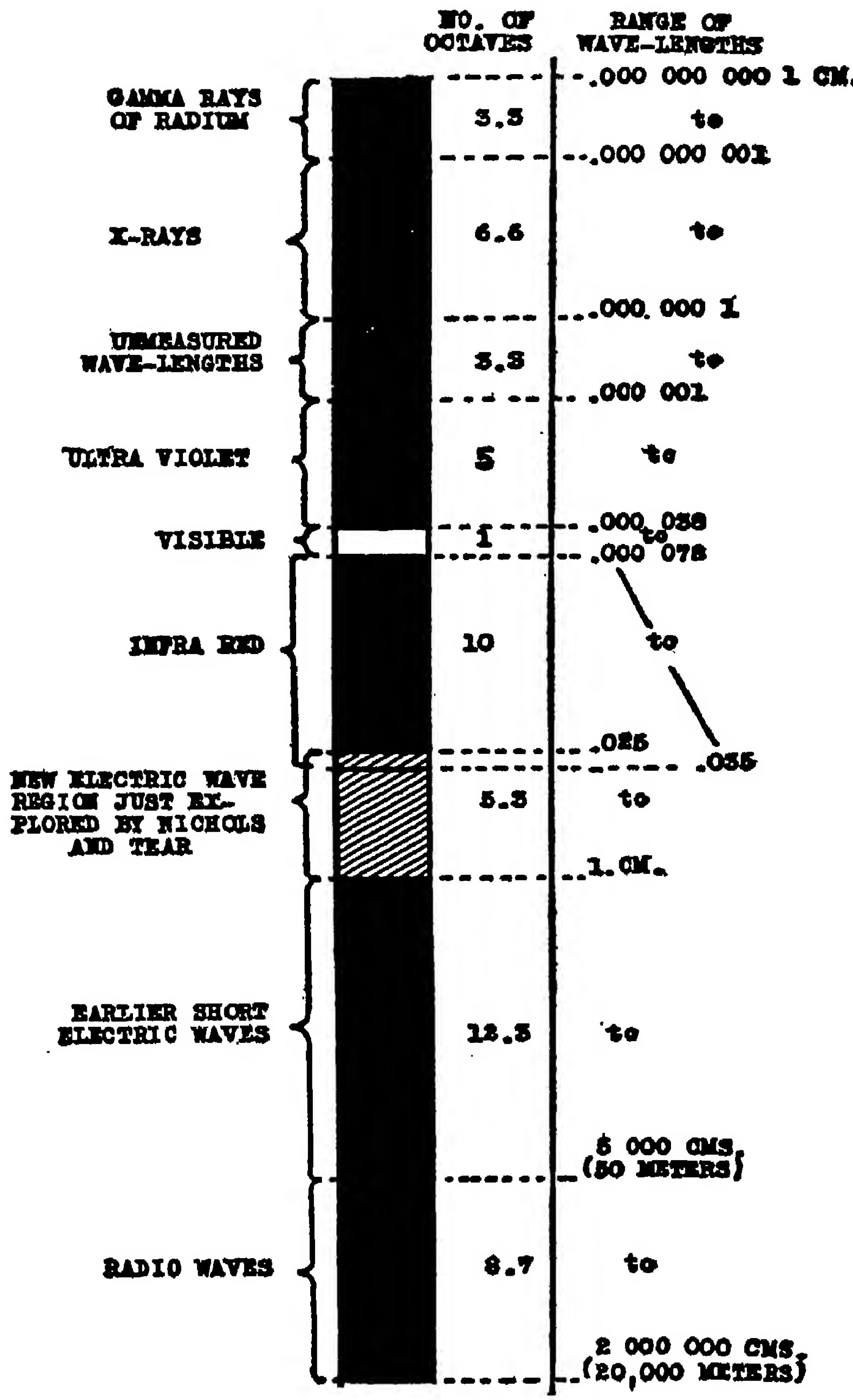


Fig. 21. Chart of the complete spectrum, showing the new electric wave region just explored by Nichols and Tear.

The entire length of the visible spectrum, from red to violet, is comprised in the narrow white region just above the middle of the chart. The immense range of the complete spectrum is thus apparent, especially when the extremely short waves, since studied by Millikan, are added above the top of the diagram.

presentation, after having described his success in producing the only type of waves previously undiscovered in this long sequence, he quietly sank to the platform and died. Such a passing, under the dome of the Academy's superb new building, dedicated on the previous day by the President of the United States to science and research, was the fitting culmination of a life devoted to the increase of knowledge. To Nichols, as we shall see in the course of this chapter, we owe some of the most important advances in the study of radiation and the first successful measures of the heat of the stars.

HEAT FROM THE STARS

Sir William Huggins, the great pioneer in astrophysics, was the first to attempt to measure the heat radiation of the stars. His discoveries with the spectroscope had taught him the advantage of utilizing laboratory instruments in the observatory, and he accordingly attached a delicate thermocouple (a junction of two metals very sensitive to radiant heat, see page 51) to his 8-inch telescope, in 1869. Some of the brightest stars, when focussed on the thermocouple, seemed to give indications of heat radiation, but their accidental origin became evident twenty years later when Boys failed to detect stellar heat with far more sensitive instruments.

Thus matters stood in 1898, with no evidence of success after several serious attempts to measure the heat radiation of stars. The Yerkes Observatory (of which I was then director) had just been

completed, and Nichols was developing the radiometer which, in the special form given it later, served so successfully in the classic investigations

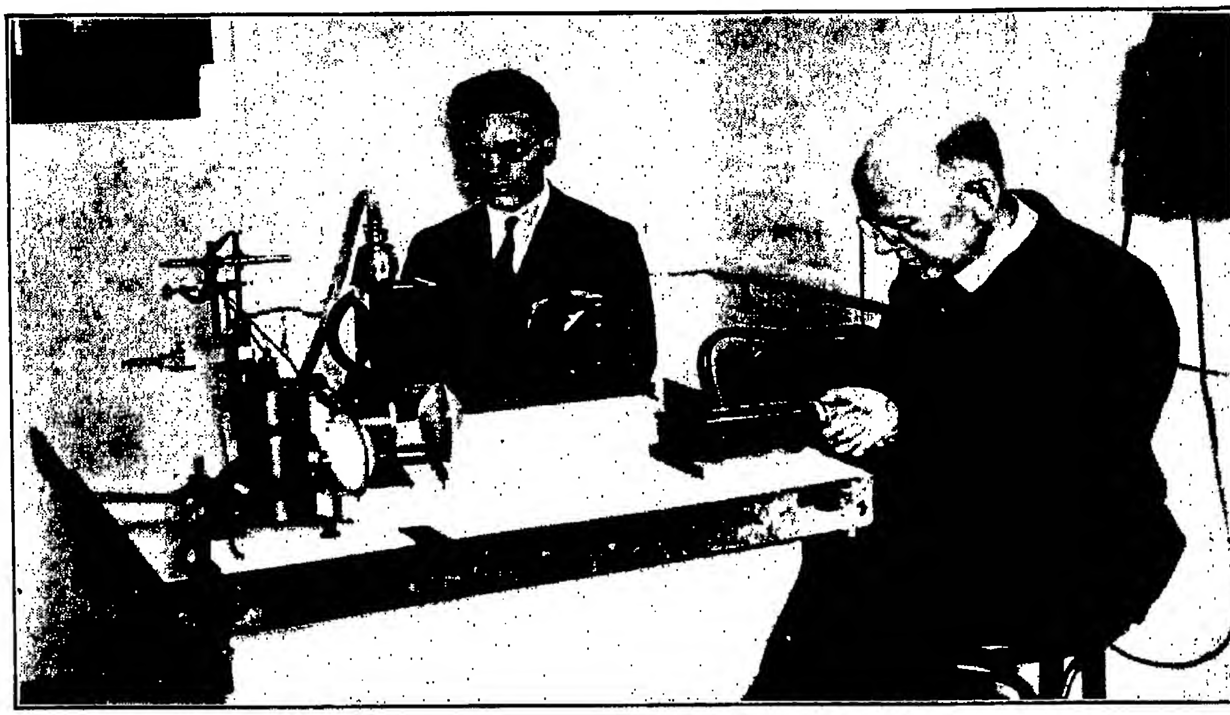


Fig. 22. Ernest Fox Nichols and his assistant, Doctor Tear.
The apparatus shown is that used in the exploration of the new electric wave region indicated in Fig. 21.

of Nichols and Hull on the pressure of light. It was already beautifully adapted for refined radiation measures, and as it greatly surpassed the best previous devices for this purpose, I invited Nichols to try it at the Yerkes Observatory during the summer of 1898 for the detection of stellar heat.

The special radiometer which he built for the purpose was an instrument of extreme sensitiveness. Its delicate mica vanes, suspended in a vacuum, received the star's image, given by a 24-inch concave mirror, after reflection from the mirror of a clock-

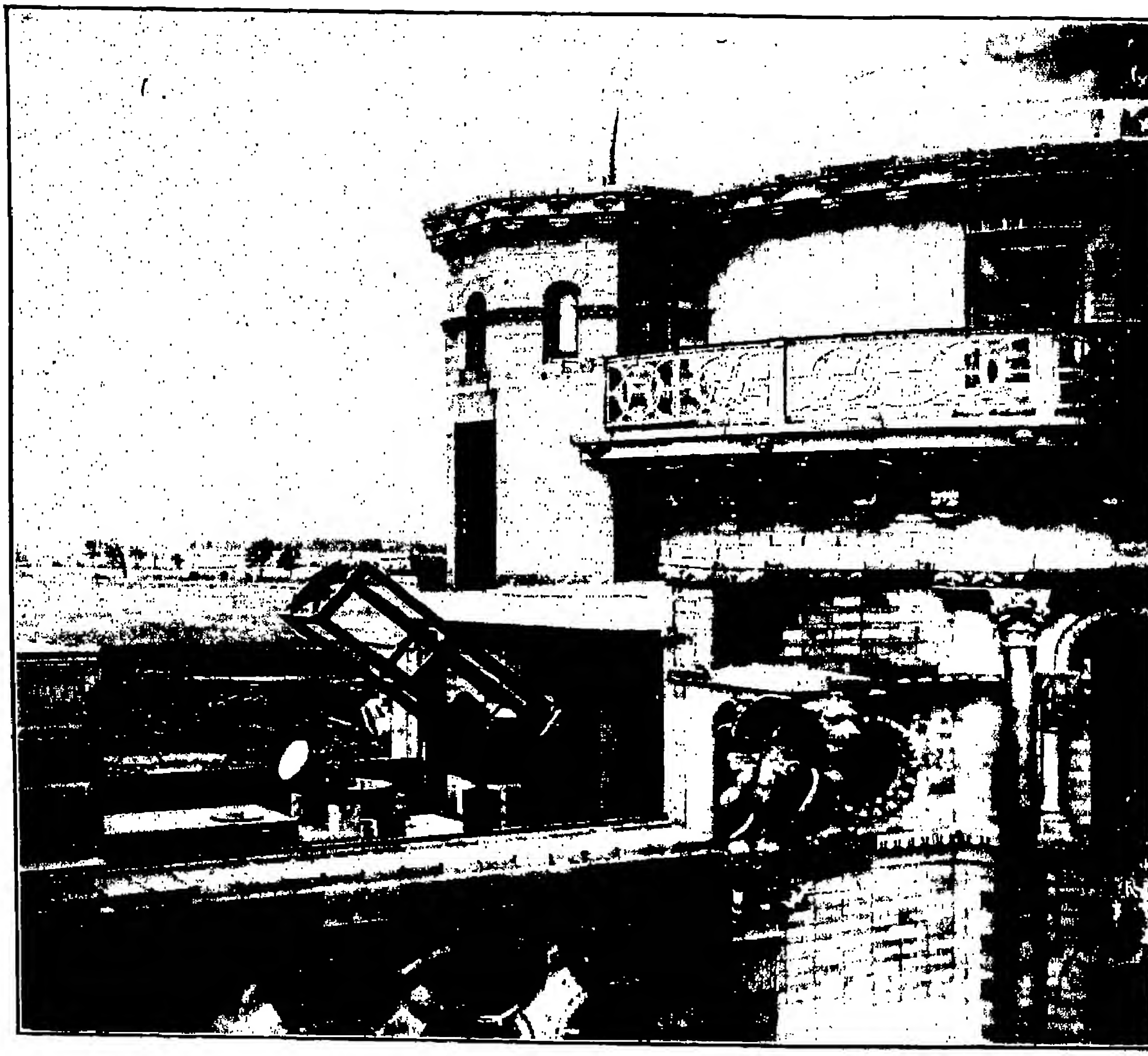


Fig. 23. Heliostat room of the Yerkes Observatory, where Nichols made the first measurements of stellar heat.

Light from the stars was reflected by the circular heliostat mirror to a concave mirror which formed the stellar image on the radiometer vane. (The larger instrument above the heliostat was not employed for this work.)

driven heliostat mounted between the north and south domes of the observatory. By moving the heliostat mirror, the star's image could be thrown on or off the vanes, and the resulting deflection could be measured by observing through a small auxiliary telescope the image of an illuminated scale

reflected from a minute mirror attached below the radiometer vanes.

A standard candle, at a distance of about 27 feet, was used to test the sensitiveness of the radiometer. Additional means of testing, and also of measuring the loss of heat caused by absorption in the earth's atmosphere, were afforded by the observation of standard candles mounted in tents at distances of 2,000 feet and 4,500 feet respectively. To give an idea of the sensitiveness of the apparatus, it may be said that the average deflection for a candle in the nearer tent, 2,000 feet away, was 67 millimetres (the apparent motion of the scale in the auxiliary telescope). One evening Doctor St. John, who was in this tent, extinguished the candle and placed his head in front of the candle-box when the signal to expose was given. The observed deflection, due to the heat radiation of his head at a distance of 2,000 feet, was 25 millimetres, repeatedly checked! In fact, the sensitiveness of the apparatus was so great that, if there were no loss due to the absorption of the intervening air, the number of candles in a group at a distance of about sixteen miles could be determined from the average of a series of measures. The radiometer employed was found to be twelve times as sensitive as the radiomicrometer of Professor Boys, and this advantage, combined with the increase in diameter of the concave mirror from 16 inches to 24 inches, sufficed to make possible the first successful measures of stellar heat.

The average deflection produced by the bright

star Arcturus, combining the observations of 1898 with those made with somewhat improved apparatus in 1900, was 1.08 millimetres. Vega, a star of equal brightness but bluer in color, gave an average deflection of 0.52 millimetres. Allowing for their difference in altitude, which involves a difference in atmospheric absorption, Nichols found that the total radiation of Arcturus was 2.2 times that of Vega. As these stars are of equal brightness to the eye, this means that Arcturus sends us more invisible rays from the infra-red region. This result, as Nichols pointed out, may be accounted for by the fact, now abundantly confirmed, that Arcturus, though of lower temperature than Vega, and therefore sending us a greater proportion of the longer wave-lengths, is so much greater in diameter as to give us about twice as much total radiation.

The pioneer results of Nichols, who also succeeded in measuring the heat radiation of Jupiter and Saturn, opened a new and very important field of astrophysical research. They pointed to the existence of comparatively cool stars whose radiation might be chiefly of the invisible sort, and they hinted at the possibility of determining a star's diameter from a study of its heat radiation. Both of these possibilities have now been realized.

THE WORK OF PFUND AND COBLENTZ

I wish that time and space permitted me to describe in these pages the whole progress of modern astronomy. All I can hope to do, however, is to tell

of some of the principal advances of my associates, with such historical background as to render their significance clear. But before passing on to recent work at Mount Wilson a word must be said of the important progress achieved by Pfund and Coblentz, who perfected the thermocouple, and applied it with marked success to the measurement of stellar heat.

The thermocouple is based upon a discovery made by Seebeck in 1822. He found that if two different metals fixed in contact are at different temperatures, an electric current is produced. Nobili, who had devised a sensitive galvanometer for the study of feeble currents, applied the thermocouple, with its aid, to the measurement of small temperature changes. In 1895 the Russian physicist Lebedew found that a thermocouple made of iron and the alloy constantan was more sensitive in a vacuum than at atmospheric pressure. Pfund made effective use of this principle in 1913 at the Allegheny Observatory, where he was very successful in measuring stellar heat radiation with a 30-inch reflecting telescope.

A year later Coblentz, of the Bureau of Standards, made another important advance at the Lick Observatory, where his improved vacuum thermocouple, employed with the 36-inch Crossley reflector, enabled him to measure the heat radiation of 105 stars. The variation of the heat radiation with the spectral type of the star, indicated by the results of Nichols for Arcturus and Vega, was beauti-

fully shown by his results, which reached stars as faint as magnitude 6.7, just beyond the range of the naked eye. His most important conclusion is that "red stars emit 2 to 3 times as much total radiation as blue stars of the same photometric magnitude." In 1921, following up at Flagstaff some experiments begun at Mount Hamilton, Coblentz studied the relative proportions of radiations of different wave-lengths by means of absorbing filters, and thus obtained estimates of the temperatures of 16 bright stars.

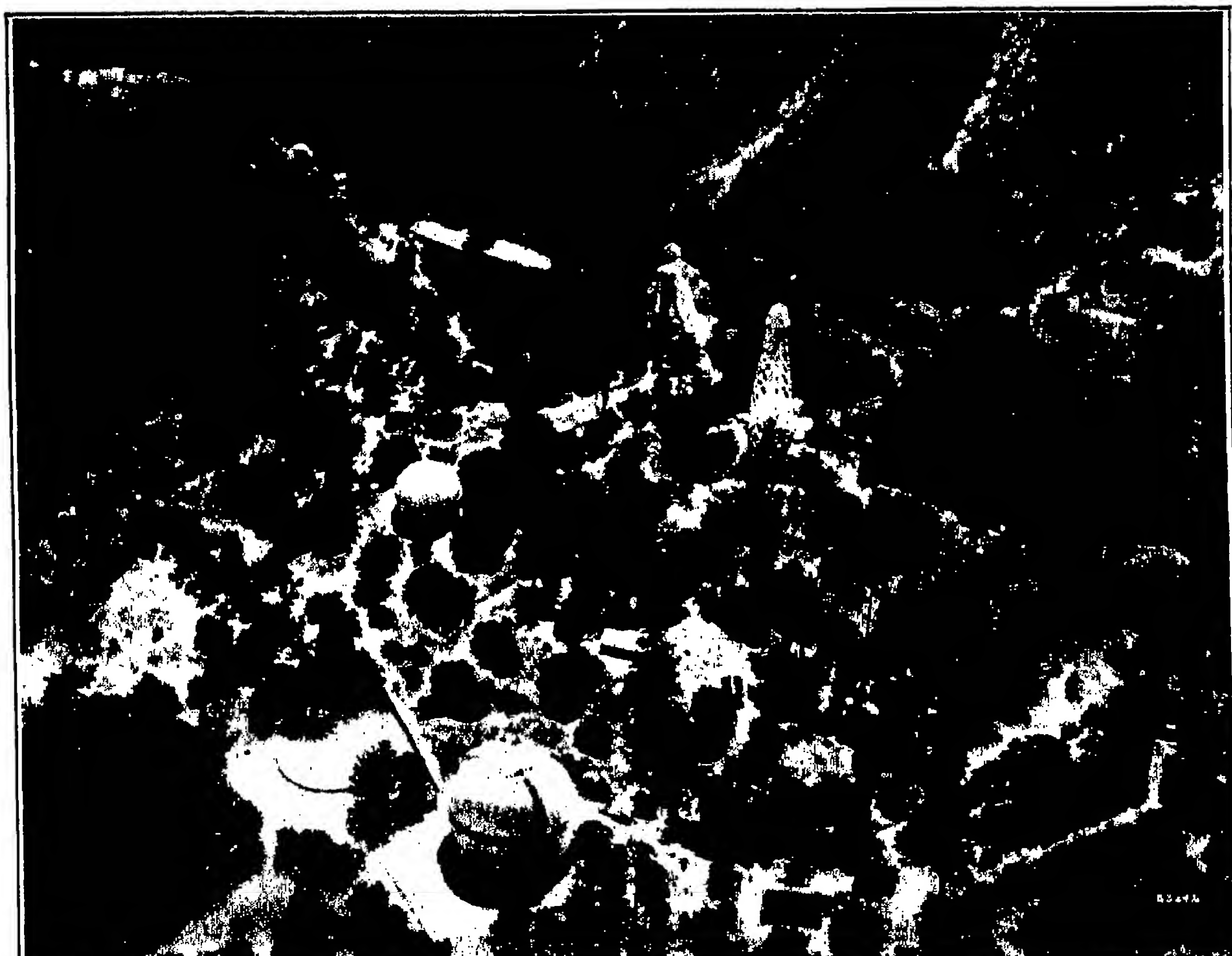
OBSERVATIONS WITH THE 100-INCH HOOKER TELESCOPE

The Hooker telescope on Mount Wilson* is admirably adapted for the measurement of stellar heat. Its concave mirror, 100 inches in diameter, collects more than seventeen times as much light as the 24-inch mirror used by Nichols at the Yerkes Observatory, and its optical and mechanical perfection permit observations to be made with far greater ease and certainty than was possible with the apparatus then available. It is astonishing to realize, however, that Pettit and Nicholson, using with this telescope improved vacuum thermocouples of their own construction, have been able to measure the heat radiation of one star as faint as the thirteenth magnitude—not far above the limit of visibility in Herschel's 20-foot telescope! Moreover, with a star of the type of X Cygni at minimum brightness (see

* Described in "The New Heavens," p. 18.

p. 56), it would be possible to reach five magnitudes fainter.

When employed for the measurement of the heat



From an official photograph, U. S. Army Air Service.

Fig. 24. Airplane view of the summit of Mount Wilson.

In the foreground is the 100-foot dome of the Hooker telescope. The dome of the 60-inch telescope is near the centre of the picture, with the 150-foot tower telescope to the right. Beyond is the 60-foot tower telescope, projected against the horizontal Snow telescope house. To the left are the laboratory, power-house, dome of the 10-inch photographic refractor, the "Monastery," and the station of the Smithsonian Astrophysical Observatory.

radiation of stars, the thermocouple is mounted at the upper end of the tube of the Hooker telescope, in the focus of the 100-inch mirror. The deflections

of the galvanometer produced by the star's heat are recorded photographically, and under favorable con-

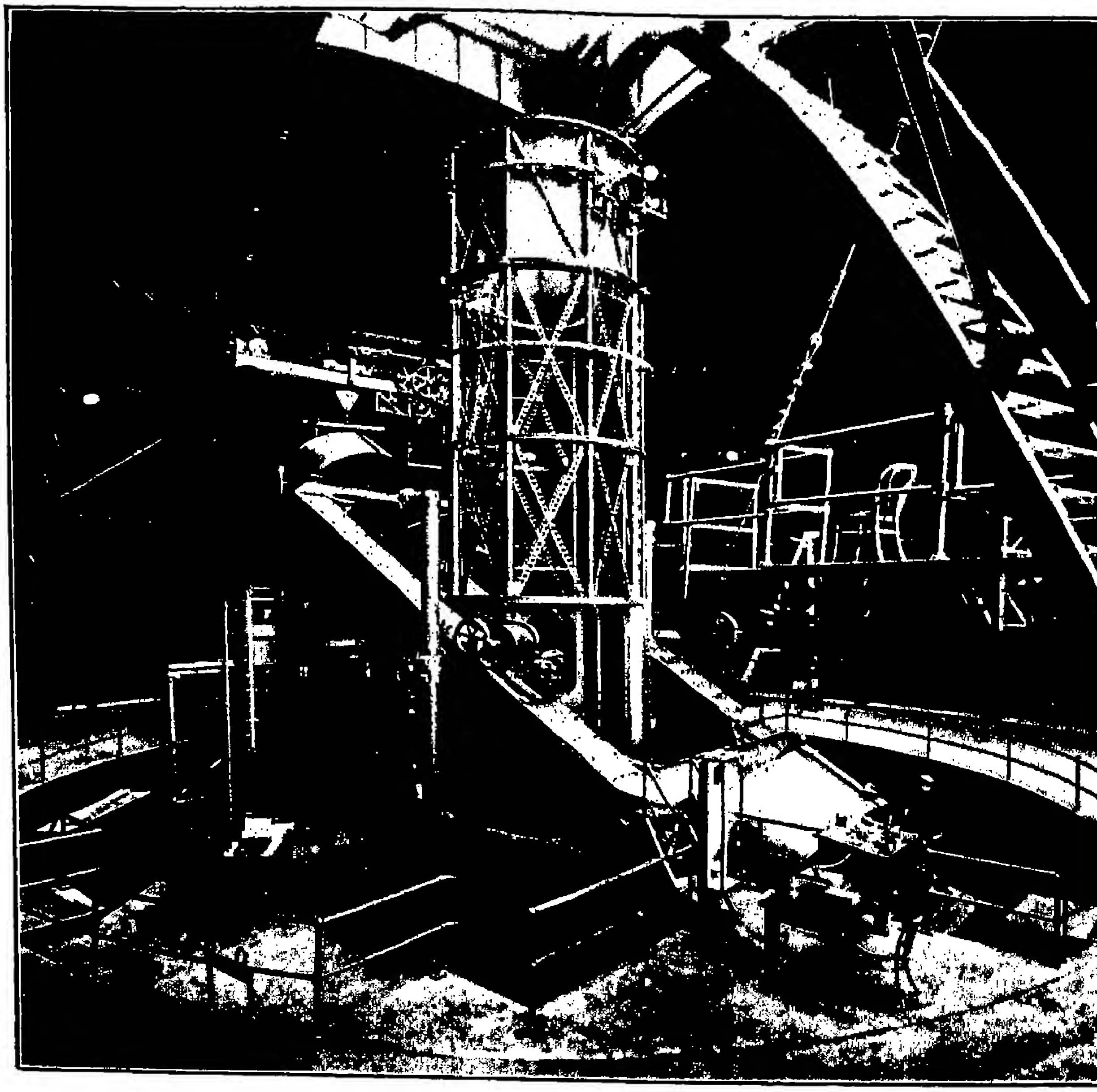


Fig. 25. The 100-inch Hooker telescope used by Nicholson and Pettit, and also by Abbot, for the measurement of stellar heat.

ditions they can be measured with extremely small errors. As the atmosphere forms only a thin shell around the earth, its absorption decreases rapidly

from low to high altitudes. This means that as a star rises from the eastern horizon toward the meridian, it constantly appears to grow brighter. The sensitivity of the thermocouple is so great that in the case of bright stars at low altitudes the resulting change in brightness in one minute can be detected. Thus under such circumstances the limit of precision in the measurements is set by the difficulty of correcting for the exact loss due to absorption by our atmosphere.

The thousands of observations made with this apparatus by Pettit and Nicholson during the last four years have led to many important conclusions. In harmony with the results of Nichols and Coblentz, the proportion of radiations of great wavelength (infra-red) emitted by the stars is found to increase with their spectral type. That is to say, the redder the star the greater the proportion of invisible heat radiation it sends us. In the case of red variable stars like Omicron Ceti this effect is surprisingly large. Thus at its minimum brightness, when beyond the reach of a telescope less than 3 inches in aperture, this variable sends us 1,300 times as much heat as a white star (type A0) of the same brightness. As the variable is so faint visually, it will be seen how great a proportion of invisible infra-red radiation it must emit at such times. But Omicron Ceti is outdone by X Cygni, a variable star ranging from the fourth to the fourteenth magnitude. Observations show that while to the eye X Cygni is 10,000 times as bright at maximum

as at minimum, the total radiation as measured with a thermocouple undergoes a variation of only 1.7 times. At minimum brightness X Cygni emits

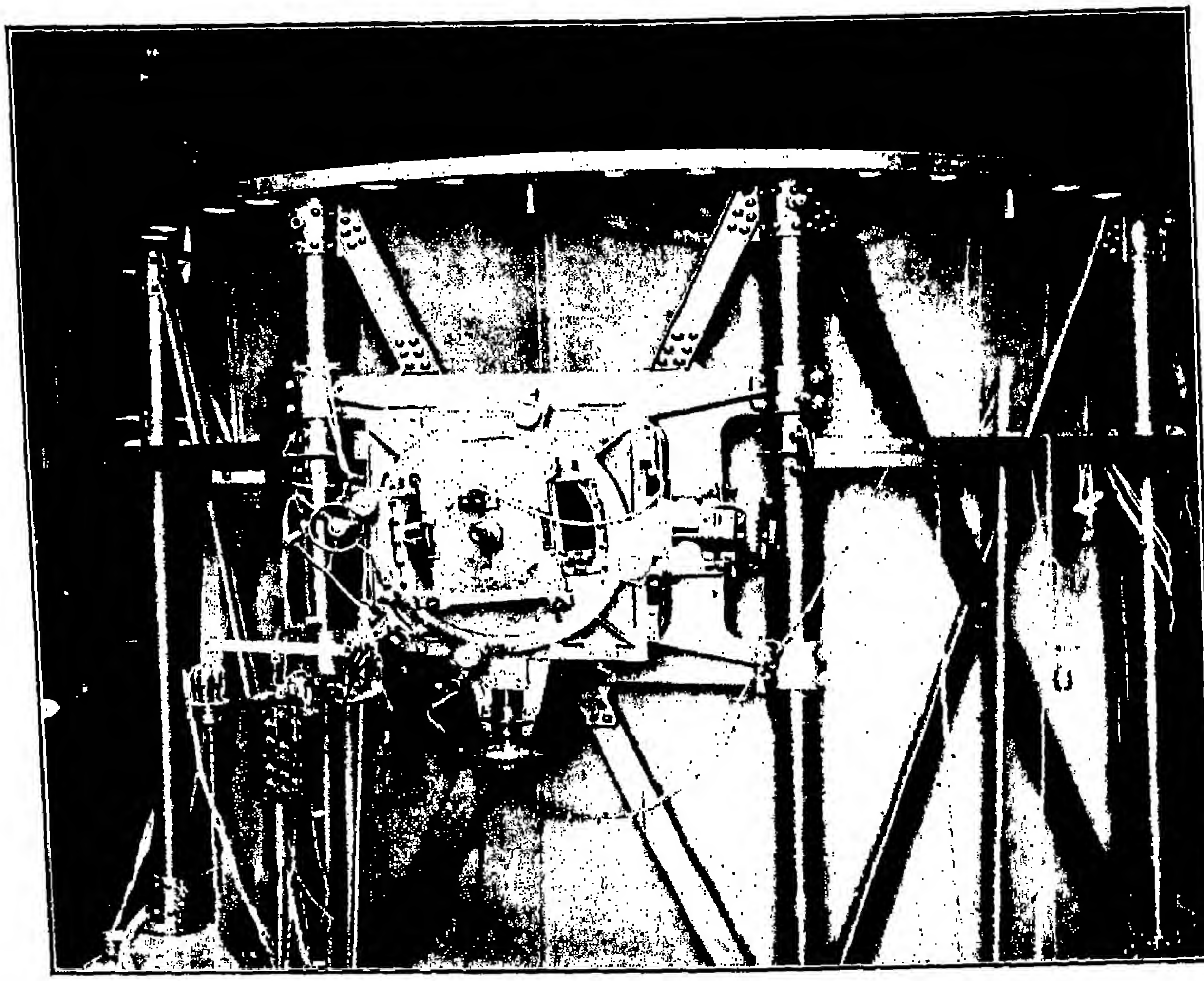


Fig. 26. Upper end of the tube of the Hooker telescope with thermocouple attached.

50,000 times as much heat as a white (Ao) star of the same magnitude. Its diameter must therefore be enormous. The possibilities of the thermocouple used with the 100-inch telescope, which is sensitive enough to detect the heat of a candle 100 miles away if there were no loss due to absorption by

the intervening atmosphere, are well illustrated by these results.

RECENT ADVANCES BY ABBOT

The success of Abbot's studies of the solar spectrum on Mount Wilson led to a trial of the bolom-

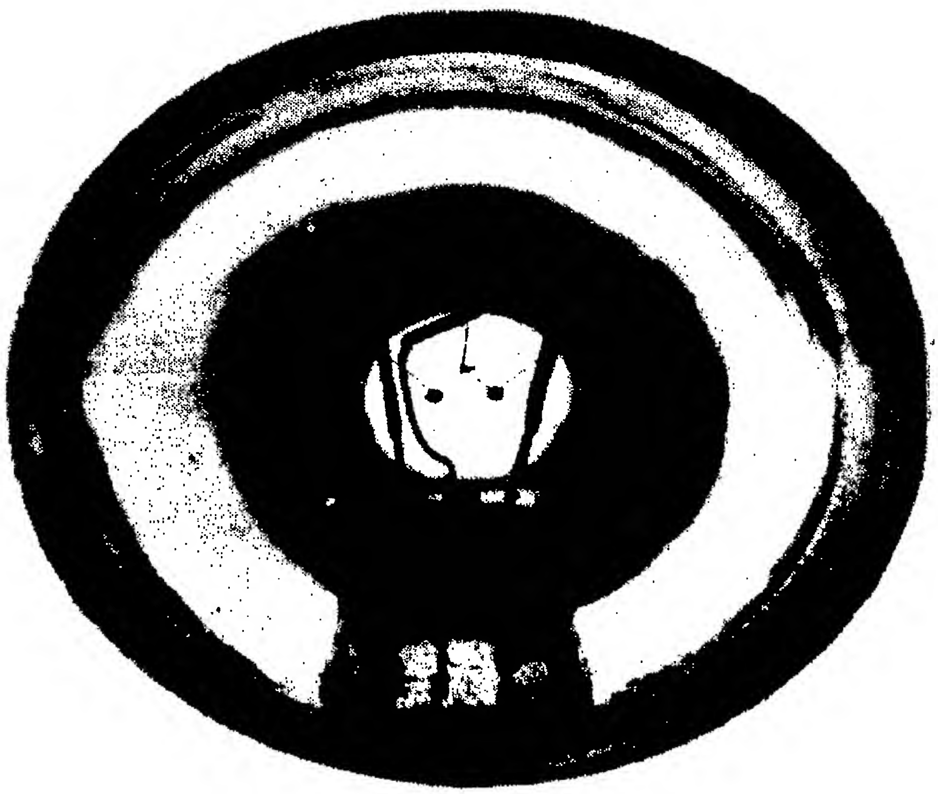


Fig. 27. The junctions of the vacuum thermocouple, as seen through the eye-piece.

Galvanometer deflections in opposite directions are obtained by setting the star first on one junction and then on the other.

eter (another instrument for measuring feeble heat radiation) for similar investigations of the spectra of bright stars. In his preliminary observations with the 100-inch telescope in 1923 he succeeded in making an approximate examination of ten stellar spectra. But the bolometer proved to be hardly ade-

quate for this difficult task, and a Nichols radiometer was chosen to replace it. This delicate instrument, built under Doctor Nichols's direction by Doctor Tear, has proved to be a marvel of efficiency. Retaining the great steadiness necessary for measures of precision, it is nevertheless fully fifteen times as sensitive as the stellar radiometer used at the Yerkes Observatory. Combining with this the advantages to be expected from the large aperture and stable mounting of the telescope, the altitude and clear sky of Mount Wilson, and certain minor instrumental improvements, a thousandfold gain in effective sensitiveness appeared probable. In spite of the great weakening of the radiation caused by dispersing the star image into a spectrum, Abbot believed that energy curves showing the intensity of radiation in various parts of the spectrum might be obtained for some of the brighter stars.

Observations were made of nine bright stars in October, 1923. The resulting energy curves, after correction for the absorption of the earth's atmosphere and the utilization of certain visual observations of the brightness of these spectra in the visible region, are shown in Fig. 28. This illustration, for the sake of economizing space, contains two sets of curves, one (to the left) referred to the horizontal wave-length scale at the bottom of the figure, the other referred to the scale four squares above it. In both cases the infra-red region is on the right, the visible spectrum extending only from 0.4 to about 0.8.

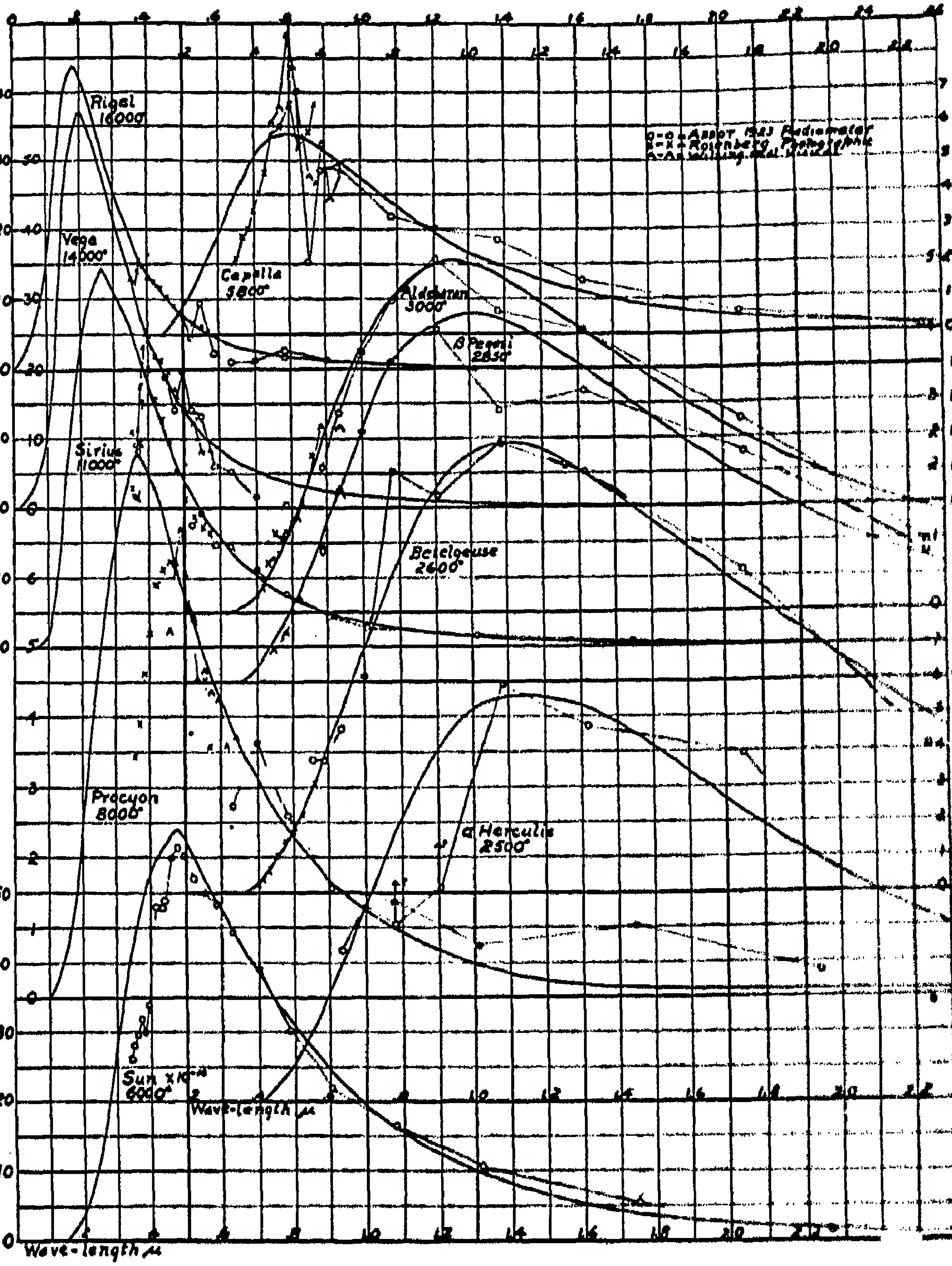


Fig. 28. Abbot's energy curves of stellar spectra.

The height of the curve measures the intensity of the radiation at the corresponding point in the spectrum. The maximum of intensity, far in the ultra-violet for the very hot star Rigel, moves steadily toward the red in stars of lower and lower temperature.

The height of the curve measures the intensity of the radiation at the corresponding point in the spectrum. It will be seen at once that the maximum, which is in the ultra-violet, far beyond the violet limit of the visible spectrum in the case of the bright bluish-white star Rigel in the constellation of Orion, moves steadily toward the right in the following stellar sequence: Rigel, Vega, Sirius, Procyon, the Sun, Capella, Aldebaran, Beta Pegasi, Betelgeuse, and Alpha Herculis. In the last four stars the most intense point in the spectrum is beyond the red limit, in the infra-red.

This change in the position of maximum intensity has a simple and definite meaning, of the greatest interest. Take a bar of iron and heat it in the fire. It gets very hot long before it begins to emit dull-red light. Finally, when greatly heated, it becomes "white hot." During the heating the point of maximum intensity in its spectrum, at first far out in the infra-red, steadily advances from the invisible infra-red toward the visible red and then on toward the violet.

The corresponding differences found by Abbot in the stars, and confirmed by other observers in a different way, may be similarly interpreted. Along the route from Alpha Herculis to Rigel the surface temperature steadily rises from about 2,500° to about 16,000° C. (see Fig. 28), and the color changes from red to bluish-white. We are thus observing, with the aid of a new device, the predicted progress of stellar evolution.

These results are not given by Abbot as final, but they are at least approximately correct, and they certainly represent great progress in astrophysical research. Making due allowance for the necessity of future revision when additional measures become available, Abbot has also deduced provisional diameters of these stars from his measures (supplemented by the visual observations of Wilsing and his associates and the photographic observations of Rosenberg), with results that are in most cases of the same order of magnitude as the interferometer measures of Michelson and Pease* and the theoretical determinations of Russell. Sirius and Procyon are found to be of about the same size as the sun, while the other stars observed range from twice to 500 times the sun's diameter. Let us see how these new results harmonize with the latest theories of stellar evolution.

THE LIFE HISTORY OF A STAR

Great advances in our knowledge of stellar evolution, made within the past year, now enable us to sketch more precisely the life history of a star. We see it in its extreme youth as an enormously distended mass of gas, sometimes exceeding 300,000,000 miles in diameter. The surface temperature of this red giant is comparatively low, ranging from 2,500° to 3,000° C., and the density of its outer parts is so slight as to be comparable with that of the residual gas in a vacuum tube, from

* See the chapter on "Giant Stars" in "The New Heavens."

which most of the contents have been pumped. At the centre of the star, however, the pressure must attain thousands of tons and the temperature two or three million degrees. The well-known red star Betelgeuse in Orion is an excellent example of this early stage of stellar life. Although its surface brightness is comparatively low, its great total brightness is accounted for by its immense diameter, shown by the Michelson interferometer to be more than 300 times that of the sun.

Such a star radiates much heat, slowly decreases in diameter, and increases in density. These changes are accompanied by a steady rise in temperature, which becomes greater and greater as the star changes in color from red through yellow to white. The surface temperature of the white stars may exceed 20,000° C., and their central temperature may reach 30,000,000°. After the maximum surface temperature is attained the surface temperature begins to fall, but the central temperature may remain nearly constant for a long period. The color meanwhile changes from white through yellow to red, so that at one end of the scale we have huge expanded red giants and near the other small condensed dwarfs, also comparatively cool at the surface but with internal temperatures of many millions of degrees and enormous internal pressures. The sun, which is an early dwarf star, has a surface temperature of about 6,000° C., and a central temperature perhaps as great as 30,000,000° C. Thus far the history of stellar life does not differ greatly from

Russell's theory, but some new and surprising modifications of the theory have recently become necessary.

STRIPPED ATOMS IN THE STARS

We are becoming accustomed to think of atoms no longer as fixed entities but as planetary systems, in which from one (hydrogen) to ninety-two (uranium) negative electrons whirl in their orbits about a central positive nucleus. With the aid of his "hot spark," taken in a high vacuum, Millikan has been able to strip the seven outer electrons from their orbits in the atoms of chlorine and other elements, thus reducing these atomic systems to simpler forms. A cosmic counterpart of the modern physicist would be some Titan, operating upon the solar system, hurling into space first Neptune, then Uranus, Saturn, Jupiter, Mars, the earth, and Venus, as he brought more and more powerful thunderbolts to bear upon the planets.

The spectra of the sun and stars plainly reveal the existence of similar phenomena. In the great flames or prominences which rise thousands of miles above the sun's surface, the calcium atoms are shown by the spectroscope to have lost one electron, torn from the outermost orbit. In the atmosphere of the hottest stars the loss of from two to four electrons changes the spectra of the metals so completely that all of their lines in the visible and accessible ultra-violet regions disappear, while the remaining lines, in the extreme ultra-violet, are com-

pletely shielded from our view by the absorption of their light in the earth's atmosphere. In the hottest stars only the lines of certain elements whose atoms are less easily disrupted are found in the regions open to our study.

The highest temperature attained in the atmospheres of the stars does not greatly exceed 20,000° C., whereas 300,000° C. would be needed to accomplish the effects of Millikan's most powerful sparks. Within the stars, as we have seen, the temperature rises to many millions of degrees. Under such conditions the lighter atoms must lose all their electrons, and be reduced to completely stripped nuclei, resembling the sun deprived of all the planets. The heavier elements may still retain a few of their inner electrons.

A dense body is one in which the atoms are closely packed together. In ordinary matter, with its electrons intact, this process of crowding cannot go very far, even under great pressures. The orbits of the electrons are widely separated and the outer orbit acts like an impassable boundary which cannot be broken down by any pressures attainable in the laboratory. Platinum, the densest substance we know on earth, is only 21.5 times as dense as water. But when the atoms are stripped of all or most of their electrons, as they are within the hottest stars, the gravitational pressures of hundreds of millions of tons per square inch may crowd the electrons and protons much closer together, and thus produce densities up to 100,000 times that of water.

The faint companion of Sirius is a case in point. It is one of the exceptional white dwarfs (most dwarf stars are red), of small diameter, great surface brightness, and enormous internal temperature. If Eddington's calculations are correct, its density must be about 50,000 times that of water. With such a density the lines in the spectrum ought to be greatly displaced toward the red, according to Einstein's theory of relativity. It is very difficult to photograph separately the spectrum of this faint object, because of the close proximity of Sirius, the brightest star in the sky. With the aid of the 100-inch Hooker telescope on Mount Wilson, Doctor Adams has nevertheless succeeded in photographing the spectrum of the companion and in measuring the shift of the lines. His results fully confirm Eddington's prediction. Thus we have every reason to believe that in this strange celestial object a density about 50,000 times that of water, enormously transcending anything known on earth, has actually been attained.

Until recently it has been supposed that the compressibility of a condensing star would rapidly decrease when the density began to approach that of water. But Eddington has shown that stellar atoms, reduced as they are by the loss of electrons, may have only about $\frac{1}{100000}$ of the bulk of ordinary atoms. The substance of a star may then continue to act like a perfect gas, of high compressibility, until a density greater than 10,000 times that of water is reached.

THE SLOW REDUCTION OF STELLAR MASS

Three years ago Seares found from a study of over a thousand stars of various spectral types that their masses showed a progressive decrease with increasing age, the dwarfs being of much smaller mass than the giants. He accordingly pointed out the possibility, in harmony with a suggestion made by Jeans in 1904, that the mass may decrease with loss of energy by radiation. Eddington, who has recently investigated this question, has come to a similar conclusion. He suggests that a star may gradually lose mass by burning itself away through the liberation of subatomic energy. Jeans believes that this might result from the falling together of positive and negative electric charges and their consequent annihilation, their energy being transformed into radiation. In any event, Jeans holds that a star's development must involve a steady decrease of mass. The rate of transformation of mass into radiation is fixed by the theory of relativity, which states that when a given mass is destroyed, the energy set free is equal to this mass multiplied by the square of the velocity of light. Knowing the energy radiated by the sun, Jeans calculates that the sun must consequently be losing mass at the rate of 4,200,000 tons per second. Some of the giant stars of large mass must be decreasing at 10,000 times this rate. Thus it seems probable that we must give up the old idea that a star's mass is constant, and substitute the conclusion that the red dwarf stars, after ages of

copious radiation, are so reduced in substance that their faintness is fully accounted for in this way.

The exceptional white dwarfs, in Russell's view, represent the last stage of stellar life, when the remaining material is so "intractable" that it requires an enormous internal temperature to transform it. The central temperature would therefore rise far above 30,000,000° C., and the surface temperature would return to that of the white stars or perhaps to an even higher level.

This remarkable conception of stellar development has been made possible by the powerful resources of modern physics, both experimental and mathematical. But theories are made to be tested, and without adequate means of observation their value would be lost. Thus we must depend in the final analysis upon the capacities of our instruments, which have now been augmented by the devices described in this article. In measuring the heat radiation of a star we are measuring the outpouring of its energy as it burns up its substance and passes through the various stages of its life.

In the work of the future, measures of stellar heat radiation will play an increasingly important part. We therefore owe a debt of gratitude to Ernest Fox Nichols, who not only was the first to measure the heat radiation of a star but who also devised and perfected the radiometer which in Abbot's hands has given us the last word on the subject. We are still more deeply indebted to him for his unwavering devotion to scientific research, to which

he returned again and again in spite of all obstacles and in defiance of a mortal disease. Twice drawn into administrative work, and at last permanently incapacitated by a serious organic affection, he adhered to his determination to renew research in his favorite field of radiation. Many a man of science will envy the sudden close of his life, at the very moment when his latest discoveries had made complete the long sweep beyond the infra-red spectrum. To men like Nichols, with a heart devoted to the most fundamental interests of mankind and a mind therefore concerned before all else with the advancement of truth, science owes its rise to its present heights and the world its escape from mediæval ignorance.

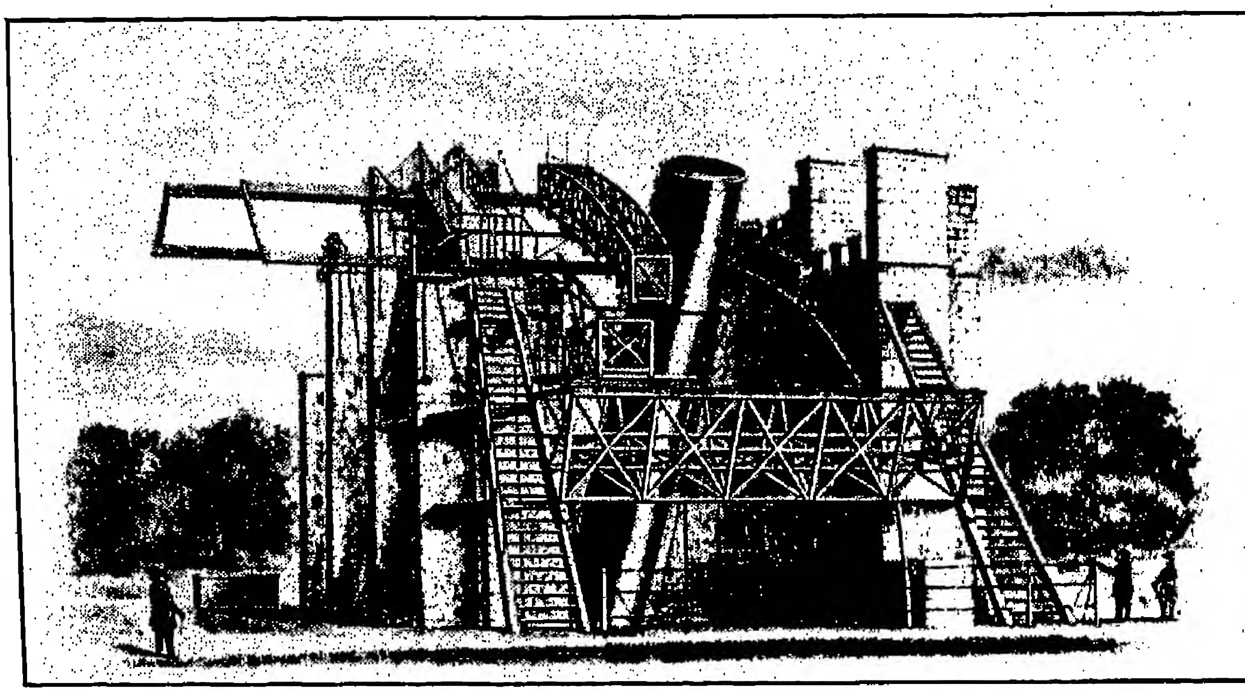
BEYOND THE MILKY WAY

"Till he heard the roar of the Milky Way
Die down and drone and cease."
—KIPLING.

THE discovery of spiral nebulæ marked an epoch in astronomical progress. We owe this advance, which initiated research in the depths of space beyond the boundaries of the Milky Way, to the enthusiasm and skill of an English peer, who overcame many difficulties in order to attain his ends.

The great telescope of Lord Rosse was built far in advance of its time. Erected in a country district of Ireland more than eighty years ago, for the most part with local labor, and lacking all the advantages which modern machine tools now afford, it must be regarded as a *tour de force* worthy of the spirit of its author. Its long tube, supported upon a ball-and-socket joint, and slung in chains between two high walls of masonry, peered precariously through the Irish mists. Lord Rosse and his associate astronomers, standing on a platform in the open air at a great height above the ground, could observe objects only when near the meridian and then at the cost of constant effort. In our modern instruments the apparent westward motion of the stars is counteracted by the steady motion of the telescope tube, turned slowly about a polar axis by a powerful driving-clock. Lord Rosse, after the tube

had been worked back and forth with a windlass until the tedious task of finding a celestial object had been completed, must then keep it in the field of view by constant recourse to similar primitive contrivances. Even if sensitive plates had been



From "A Handbook of Descriptive and Practical Astronomy," the Clarendon Press, Oxford.

Fig. 29. The Earl of Rosse's six-foot reflecting telescope.

available at that period, he could not have photographed the stars and nebulæ, which must be held absolutely fixed in position upon the plate for hours at a time. Thus it is easy to see why this great telescope could not compete in most classes of work with even a modern 12-inch reflector, properly mounted and equipped with a good driving-clock.

In spite of all mechanical, optical, and climatic difficulties, the Parsonstown reflector is to be credited with one of the capital discoveries of astronomy.

In April, 1845, scarcely two months after its completion, the huge instrument was directed to a well-known nebula in the constellation of the Hunting

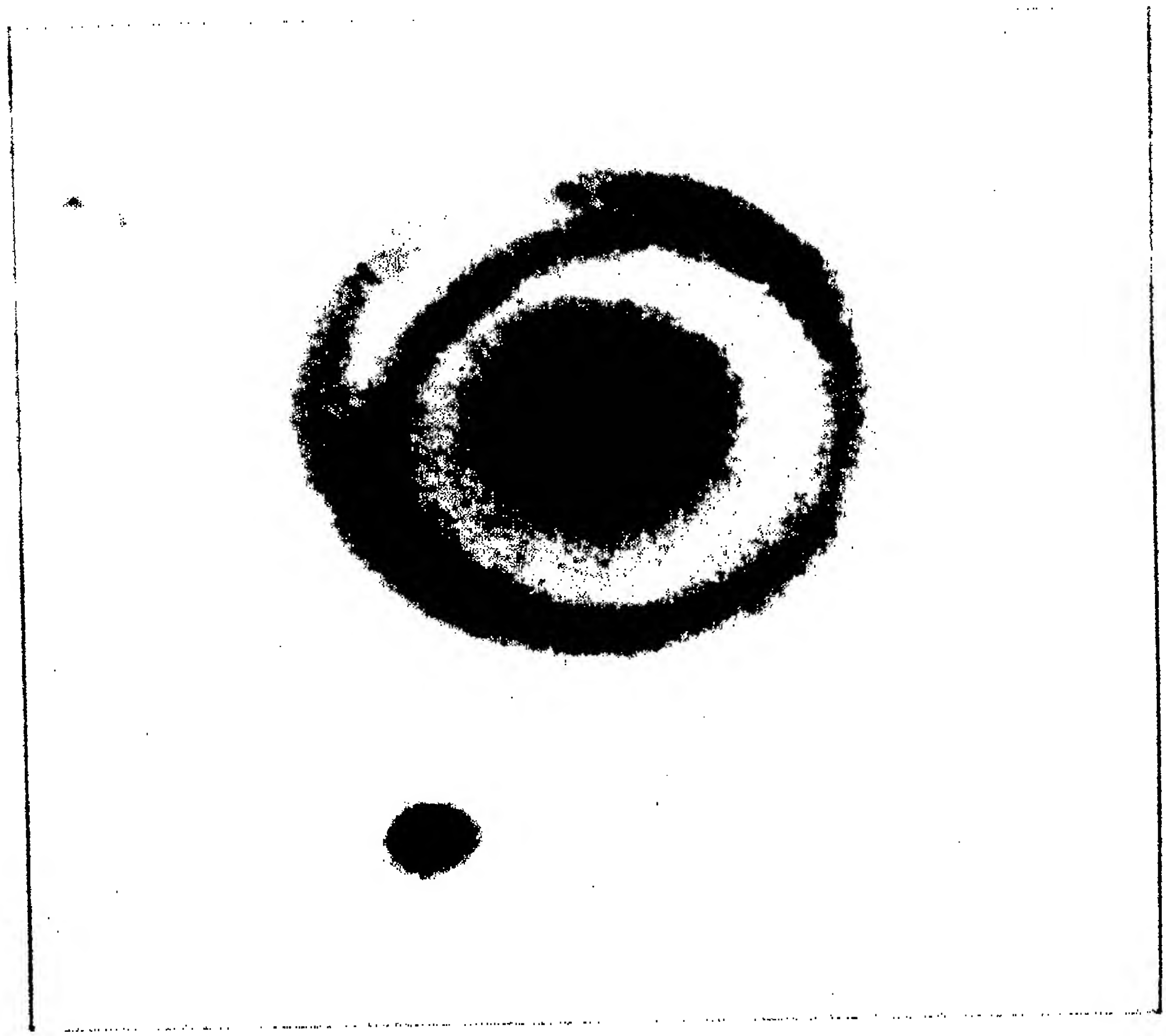


Fig. 30. Sir John Herschel's drawing of the Spiral Nebula M 51 in the constellation of the Hunting Dogs.

Dogs, near the tail of the Great Bear. As drawn by Sir John Herschel, this nebula appeared like a split ring surrounding a bright nucleus, analogous, in his view, with the structure of the Milky Way (Fig. 30).

Fig. 31. Lord Rosse's drawing of the Nebula M 51, showing its spiral form for the first time.

The 6-foot mirror revealed a very different form (Fig. 31). The spiral structure then for the first time portrayed in the heavens, abundantly confirmed by

Fig. 32. Photograph of the Spiral Nebula M 51, made by Humason with the 100-inch Hooker telescope of the Mount Wilson Observatory.

modern photography (Fig. 32), has proved to be typical of a great class of nebulæ now numbered by hundreds of thousands.

CELESTIAL OBJECTS

Our immediate neighbors in space are the members of the solar system, comprising a single star, the sun, encircled by the planets with their satellites, by swarms of meteors, and by occasional comets. Apart from these minor attendants of the sun, celestial genera are few in number. They include:

(1) The stars, which are found in all stages of development, from inflated gaseous spheres 400,000,000 miles in diameter to ancient dwarfs smaller than the sun and with densities as great as 100,000 times that of water. More than a billion stars constitute the galaxy, of which the solar system is an insignificant part.

(2) Open clusters of stars, about 200 of which have been catalogued.

(3) Globular star clusters, only about one hundred in all, each containing from 10,000 to more than 50,000 stars.

(4) Temporary stars, or "novæ," which appear from time to time, chiefly in the Milky Way.

(5) Galactic nebulæ, planetary and diffuse.

(6) Non-galactic nebulæ, chiefly elliptical and spiral.

(7) The Magellanic Clouds, which seem to be separate stellar systems, about 100,000 light-years away.*

In previous volumes many of these objects have been illustrated and Shapley's investigations on the

* The light-year is about 6,000,000,000,000 miles.

scale of the galaxy have been described.* His conclusions regarding its enormous diameter, which he placed at about 300,000 light-years, were based chiefly on his studies of the globular clusters, which he believes to outline the form and extent of the galactic system. More recent investigations at the Mount Wilson Observatory, by Seares and Kapteyn (continued after the latter's death by Seares and van Rhijn), comprise accurate measures of the brightness of 70,000 stars between magnitudes 13.5 and 18.5. They thus involve the first extensive study of the faint stars, far beyond the range of Herschel's telescope. In general they confirm the conclusions of Herschel and his successors that the galaxy is a watch-shaped aggregation of stars, with the sun at some distance from its centre. The measures "show that the stars thin out with increasing distance from the centre; that at great distances they thin out more rapidly than near the sun; and that this thinning out is most pronounced in the direction of the poles of the Milky Way—results obviously related to the flattened, watch-shaped form of the system." "The importance of the Milky Way as a structural feature of the system is also indicated by the fact that 95 per cent of all the stars are within 20° of the galactic plane." The total number of stars that can be photographed in the galaxy is about 1,000,000,000, but it undoubtedly comprises countless fainter stars. As the range

* See "The New Heavens" and "The Depths of the Universe," Charles Scribner's Sons, New York.

in intrinsic brightness among the stars is at least 100,000,000 to 1, it is impossible to estimate their distances merely on the basis of their apparent brightness. Nevertheless, Seares concludes from special studies of the intrinsic brightness of the stars in the Milky Way that the diameter of the galaxy almost certainly exceeds 100,000 light-years and may well be ten times as great.

We thus regard the sun and all other stars (excepting those in the Magellanic Clouds, in certain clusters, and in the spiral nebulæ) as members of this immense galactic system. The globular clusters seem to outline it, while the planetary and diffuse nebulæ, also among its constituents, are almost all observed in the direction of the Milky Way, not far from the galactic plane. Astronomers are generally agreed as to the composition of the galaxy, though there is still some difference of opinion regarding its dimensions. The outstanding question is the nature and distance of the spiral nebulæ and the part they play in the structure of the universe.

HERSCHEL'S NEBULÆ

The great nebula in Andromeda, so bright in its central part that it was probably detected in very early times by the naked eye, was certainly known to the Persian astronomer Al-Sufi in the tenth century. The Orion nebula, mentioned by Peiresc in 1611, was rediscovered in 1656 by Huygens, who likened it to "an hiatus in the sky, affording a glimpse of a more luminous region beyond." In

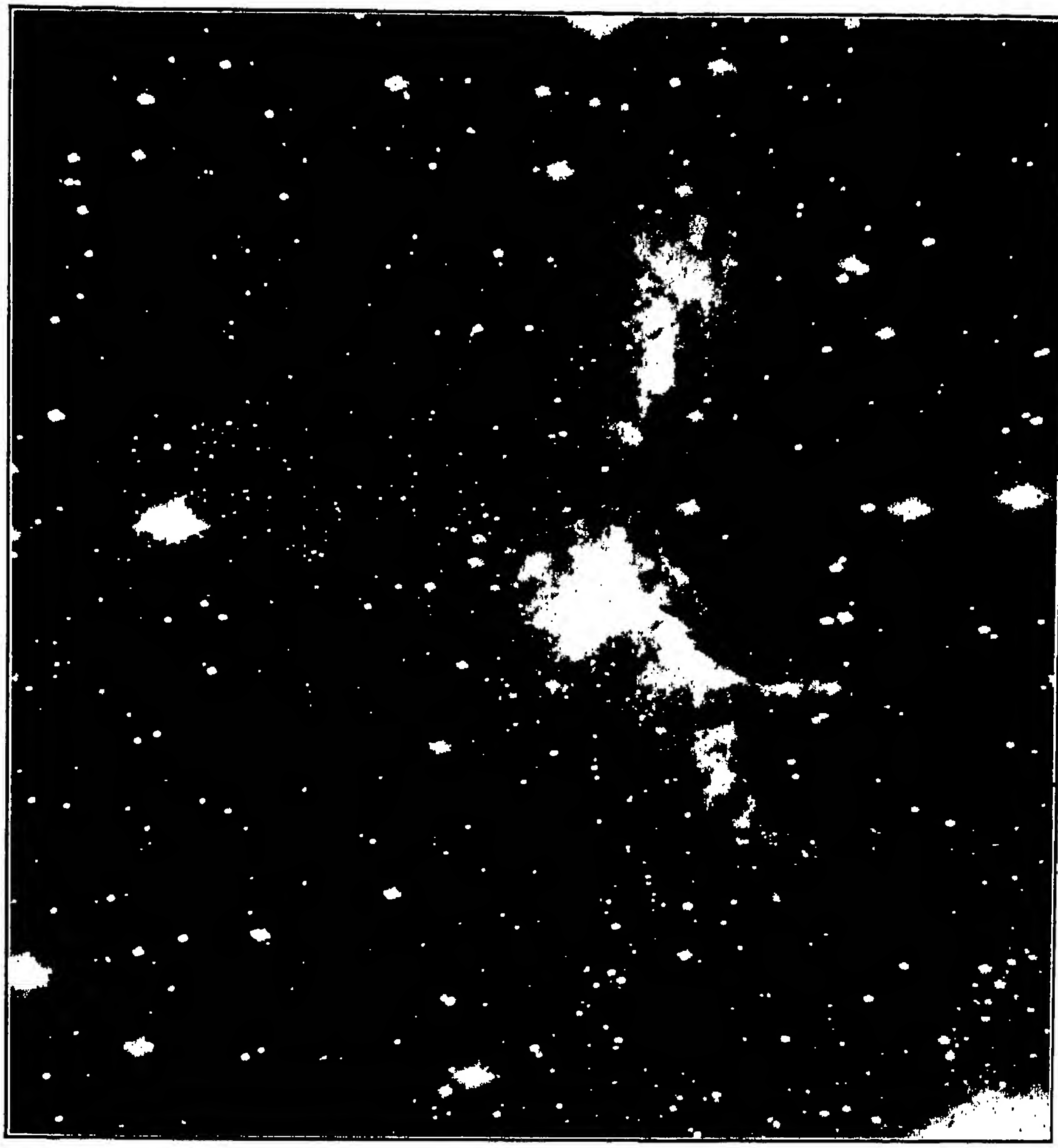


Fig. 33. Bright and dark nebulosity west of the "North America" Nebula, photographed by Duncan with the Hooker telescope.

1716 Halley knew of six nebulæ, and Lacaille published in 1755 a catalogue of forty-two others, discovered in the southern heavens during his expedition to the Cape of Good Hope. Messier,

who devoted himself to the pursuit of comets, was so frequently misled by encounters with nebulæ and clusters that in 1781 he catalogued 103 of them, which are still designated by his name and number.

It remained for the great celestial explorer, Sir William Herschel, to gather the real harvest of nebulæ and clusters with his powerful telescopes. By 1802 he had catalogued 2,500 of them, which he described in vivid terms:

"I have seen double and treble nebulæ, variously arranged; large ones with small, seeming attendants; narrow but much extended, lucid nebulæ or bright dashes; some of the shape of a fan, resembling an electric brush, issuing from a lucid point; others of the cometic shape, with a seeming nucleus in the centre; or like cloudy stars, surrounded with a nebulous atmosphere; a different sort again contain a nebulosity of the milky kind, like that wonderful, inexplicable phenomenon about θ Orionis; while others shine with a fainter, mottled kind of light, which denotes their being resolvable into stars." *

At first this question of resolvability led him to think that with sufficiently powerful telescopes all nebulæ could be reduced to stars. But in 1791, after discovering a star "surrounded with a faintly luminous atmosphere," he changed his mind. "When I pursued these researches," he says, "I was in the situation of a natural philosopher who follows the various species of animals and insects from the height of their perfection down to the lowest ebb

* Herschel's *Collected Scientific Papers*, vol. I, p. 160.

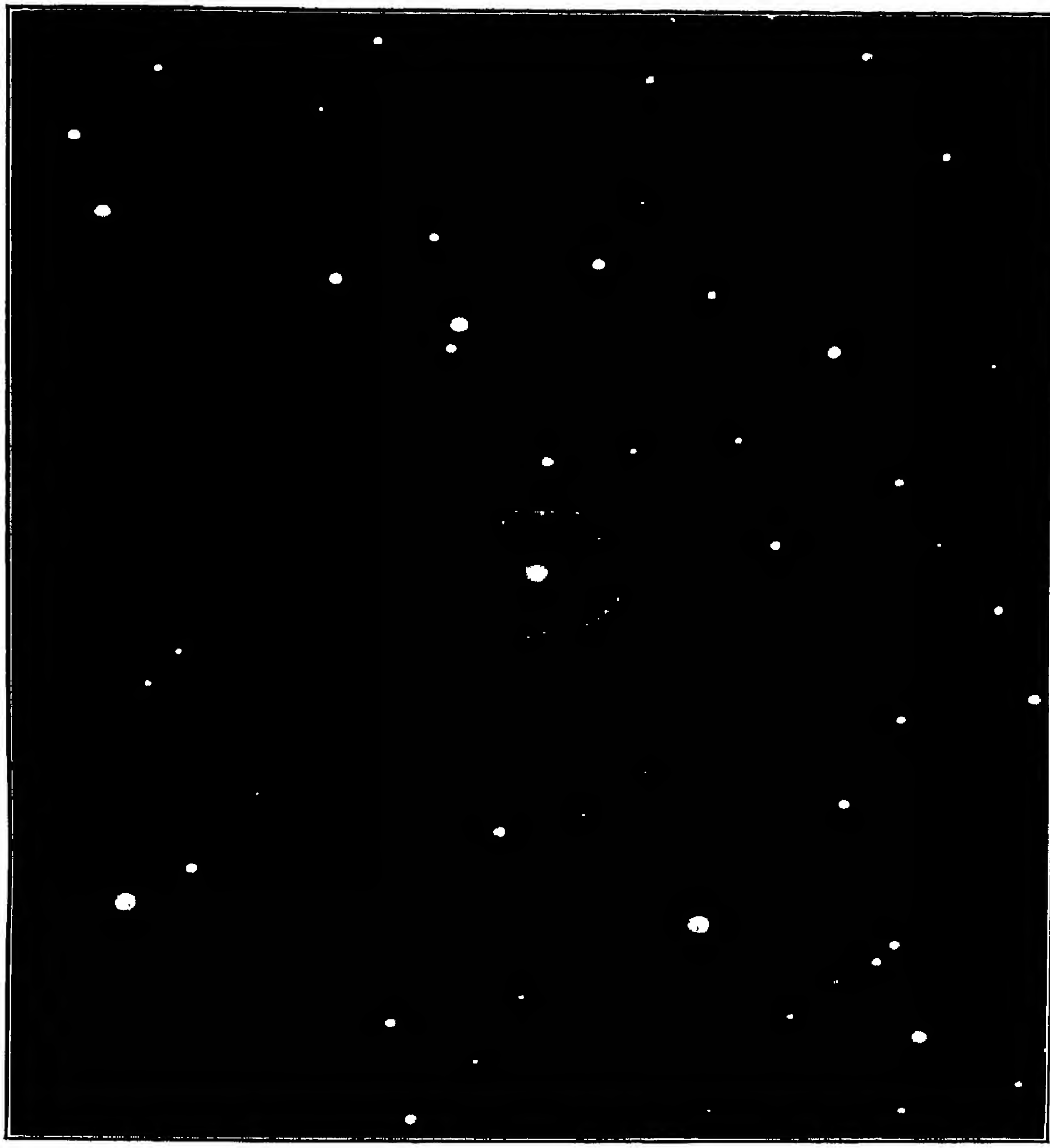


Fig. 34. Planetary Nebula N.G.C. 1501, photographed by Pease with the 60-inch reflecting telescope of the Mount Wilson Observatory.

of life; when, arriving at the vegetable kingdom, he can scarcely point out to us the precise boundary where the animal ceases and the plant begins; and

may even go so far as to suspect them not to be essentially different. But recollecting himself, he compares, for instance, one of the human species to a tree, and all doubt upon the subject vanishes before him. In the same manner we pass through gentle steps from a coarse cluster of stars, such as the Pleiades, the Præsepe, the Milky Way, the cluster in the Crab . . . without any hesitation, till we find ourselves brought to an object such as the nebula in Orion, where we are still inclined to remain in the once adopted idea, of stars exceedingly remote, and inconceivably crowded, as being the occasion of that remarkable appearance. It seems, therefore, to require a more dissimilar object to set us right again. A glance like that of the naturalist, who casts his eye from the perfect animal to the perfect vegetable, is wanting to remove the veil from the mind of the astronomer. The object I have mentioned above is the phenomenon that was wanting for this purpose. View, for instance, the 19th cluster of my 6th class, and afterward cast your eye on this cloudy star, and the result will be no less decisive than that of the naturalist we have alluded to. Our judgment, I may venture to say, will be that *the nebulosity about the star is not of a starry nature.*" *

This brilliant prediction was verified in 1864 by Sir William Huggins, the great pioneer in astronomical spectroscopy. Analyzing with his prisms the light of a planetary nebula in Draco, he saw at once

* Herschel's *Collected Scientific Papers*, vol. I, p. 415.

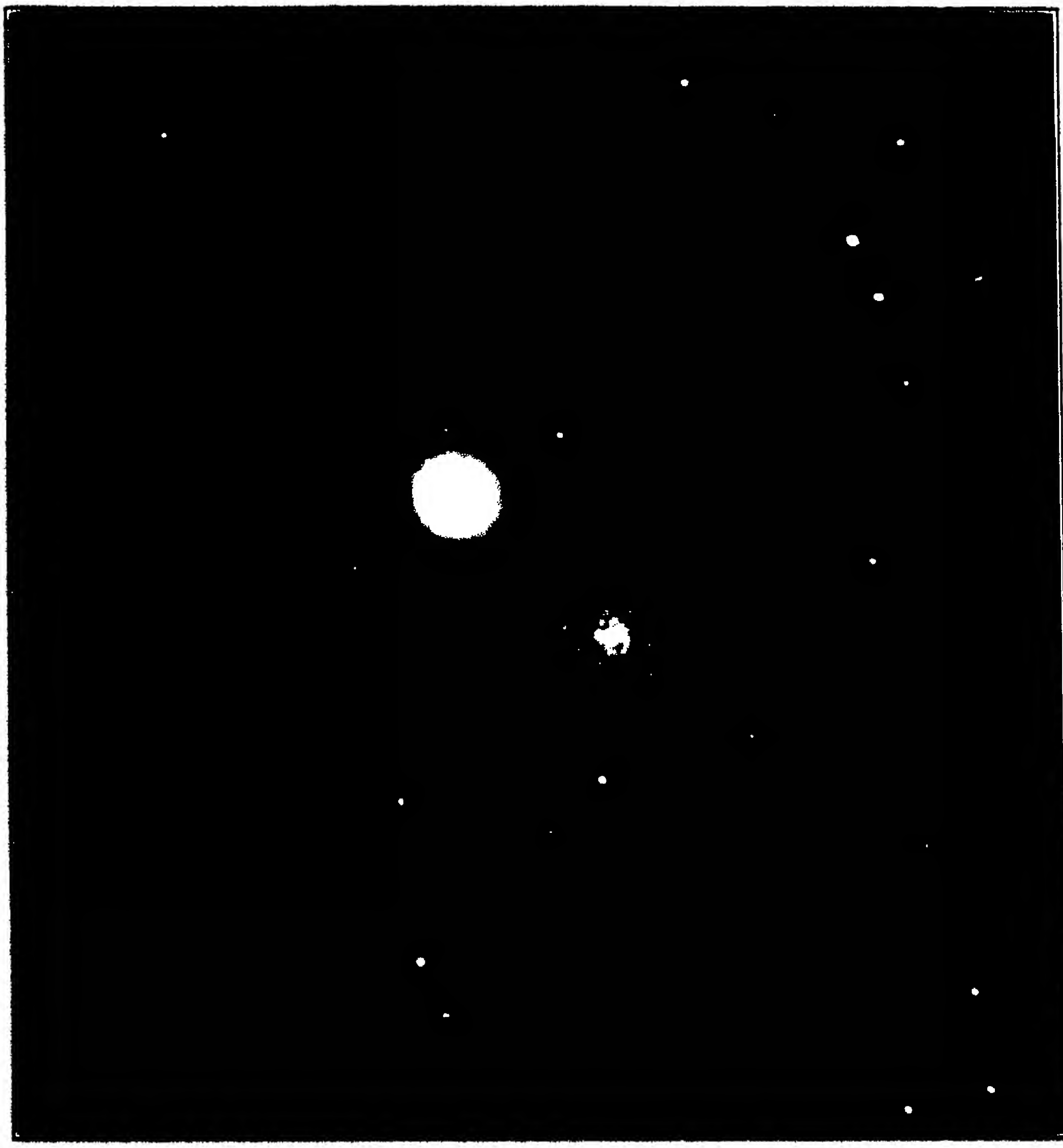


Fig. 35. Globular and spiral nebulae, photographed by Hubble with the Hooker telescope.

the bright lines characteristic of glowing gases. Subsequently he extended his researches to scores of these objects, and found fully a third of them to be of a gaseous nature. A recent interpretation of

such observations, as applied to the Orion nebula, may be found in a chapter on "Barnard's Dark Nebulæ," in "The Depths of the Universe."

In spite of Herschel's foresight, the possibility of resolving all nebulæ into stars held the attention of many astronomers down to the time of Huggins. This possibility seemed to be strengthened by the success of Lord Rosse in breaking up many nebulæ which Herschel's smaller telescopes had failed to resolve. Lord Rosse even believed he had resolved the great nebula in Orion, and Bond thought that both the Orion and the Trifid nebulæ could be separated into stars with the Harvard 15-inch refractor. Thus arose a wide-spread impression that all nebulæ are very remote star clusters. If so, their apparent dimensions would raise them to the dignity of "island universes," vastly distant in space and comparable in scale with the galactic system itself. This is the very conclusion to which Hubble has been led by his recent investigations of certain spirals with the 100-inch reflector at Mount Wilson, but it certainly does not apply to all nebulæ. Progress has been hindered by the old custom of classing diffuse and spiral nebulæ together, and by the delay in recognizing the comparative nearness of the planetary and diffuse types, most of them partly gaseous in nature and members of our own galactic system.

RECENT STUDIES OF SPIRAL NEBULÆ

The possibilities of research on the nebulæ were completely transformed by the application of pho-

Fig. 36. Central part of the Great Nebula in Andromeda, photographed by Duncan with the Hooker telescope.

tography in 1880, when Henry Draper first succeeded in recording the great nebula in Orion. Common and Roberts soon obtained better results, and in 1888 a three hours' exposure with the 20-inch

reflector of Isaac Roberts revealed for the first time the spiral nature of the great nebula in Andromeda (Fig. 36). The immense advantages of photography in the study of the structure of nebulæ have become more and more evident as sensitive plates have improved in quality and telescopes have increased in size and in optical and mechanical perfection.

So faint are the spiral nebulæ that even now the fourteen objects of this class catalogued by Lord Rosse could not be greatly increased in number by visual means. The photographic plate tells a different story. Keeler, in his extensive work with the Crossley reflector at the Lick Observatory, estimated from the numerous small spirals on his negatives that the entire heavens must contain at least 120,000 of these objects. Perrine, who completed Keeler's original photographic programme, concluded that half a million spirals were within reach of the Crossley reflector, and Curtis subsequently increased this estimate. From a recent examination of many photographs taken on Mount Wilson with the 60-inch reflector, which show stars as faint as magnitude 18.5, Seares is inclined to reduce the number of non-galactic nebulæ to about 300,000, including the true spirals and the structureless elliptical nebulæ which have often been taken for them.

Some of the spirals cover large areas in the heavens. The angular diameter of the great nebula in Andromeda is three degrees, or six times that of the moon, and M 33 is one degree in diameter. They all seem to be thin disks roughly circular in

form when seen full face, elliptical when observed at smaller angles with their central plane. One of their chief peculiarities is the great velocity with which they are moving through space, found spectroscopically by Slipher to average about 600 kilo-

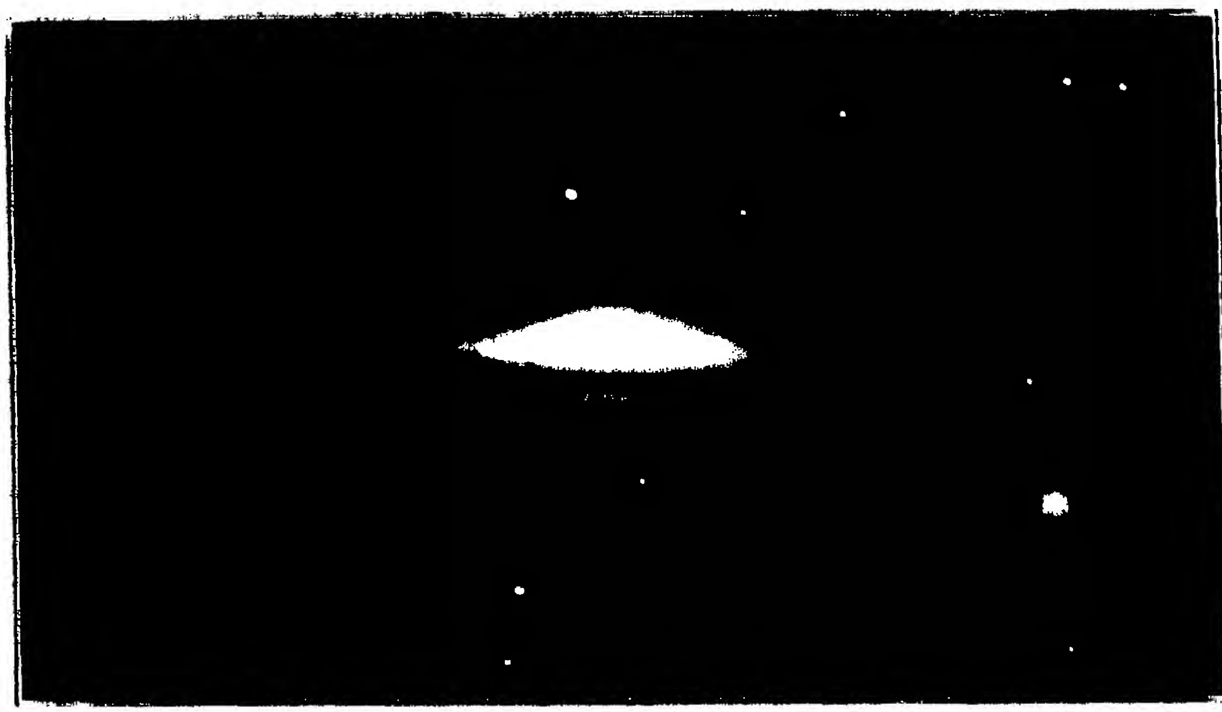


Fig. 37. Spiral Nebula N.G.C. 4594, photographed by Pease with the 60-inch telescope.

metres per second and to attain in one case 1,800 kilometres per second. These great speeds are in striking contrast with those of the stars of the galaxy, which average about 15 kilometres per second, though in a few cases stellar velocities as high as 300 kilometres per second are known. But to the eye the most striking feature of the spirals is the evidence they suggest of rapid whirling motion.

Spectroscopic observations of spirals seen on edge

fully confirm this impression. Thus a photograph of the spectrum of the spiral N.G.C. 4,594 (Fig. 37), made at Mount Wilson by Pease with an exposure of 80 hours, shows that this nebula is moving away from the sun at the rate of 1,180 kilometres per second and whirling about its nucleus at an amazing velocity. At a distance of two minutes of arc from the nucleus the rotational speed is over 330 kilometres per second. For the great nebula in Andromeda, Pease found a rotational velocity of 58 kilometres per second at a distance of two minutes of arc from the centre, and Slipher has obtained similar results. Unless the great spirals are extremely remote, we should therefore expect photographs taken five or ten years apart to show definite evidence of changes in form due to their rotation.

Such changes have been sought by van Maanen, who has made a long series of comparative measures of the same points in photographs of spirals taken at intervals of several years. The results, which apparently show definite evidence of outward motion along the arms, led him to infer that these spirals are at distances of the order of 3,000 to 30,000 light-years, and therefore lie within the galactic system. As van Maanen is unsurpassed in his skill in measurement, there can be no doubt of the existence of some form of displacement. It is difficult to conceive of systematic photographic or instrumental differences between the old and new plates which would always give an outward motion along the arms of a spiral, and the question remains whether the displacements can be accounted for by

some other obscure source of error. As matters stand, van Maanen's conclusions as to the distance and dimensions of the spirals are radically different from those of Curtis and Hubble, and much work may be needed to clear up the discrepancy.

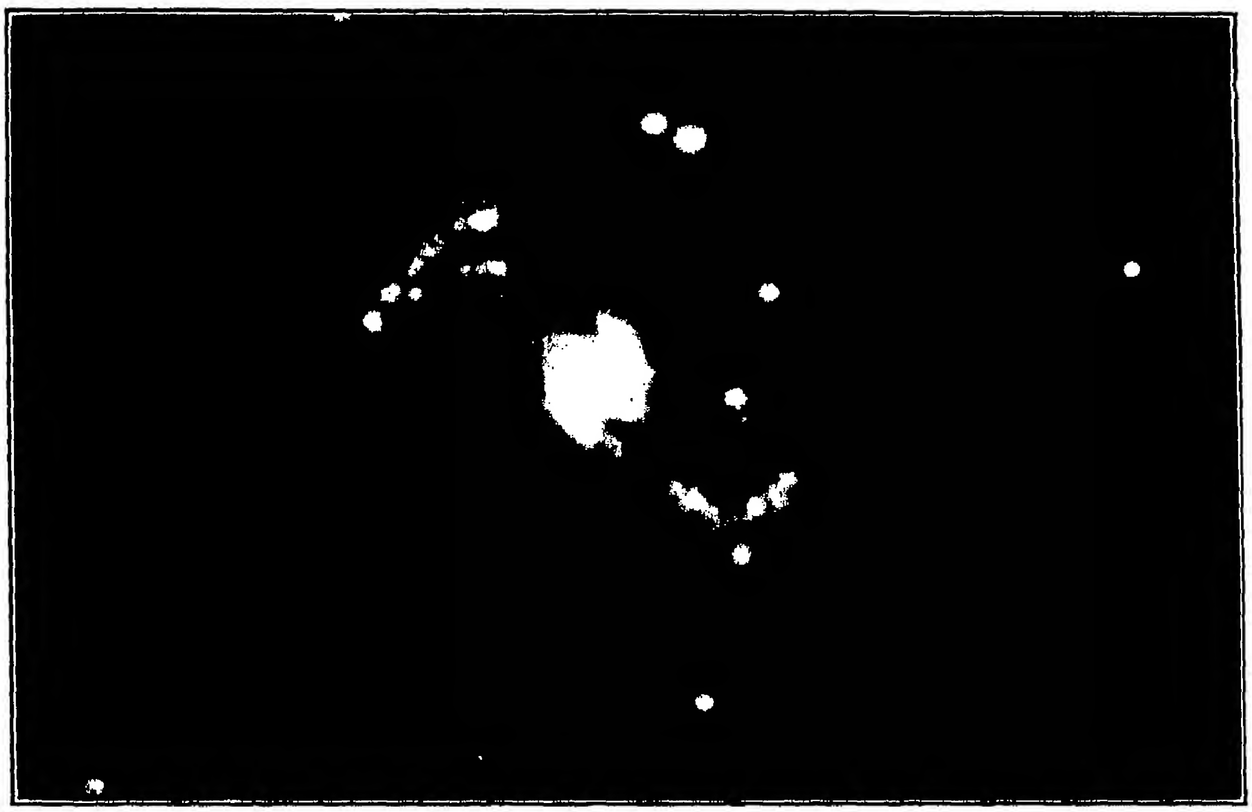


Fig. 38. Spiral Nebula N.G.C. 5383, photographed by Pease with the 60-inch telescope.

THE VIEWS OF CURTIS ON "ISLAND UNIVERSES"

In a debate before the National Academy of Sciences in 1921 with Doctor Harlow Shapley on the scale of the universe, Doctor Heber D. Curtis summarized the results of an extensive study of spiral nebulæ made at the Lick Observatory.* He strongly

* Shapley and Curtis, "The Scale of the Universe," *Bulletin of the National Research Council*, vol. II, part 3, no. 11, 1921.

favored the "island universe" hypothesis for the following reasons:

1. On this theory we avoid the almost insuperable difficulties involved in an attempt to fit the spirals in any coherent scheme of stellar evolution, either as a point of origin or as an evolutionary product.

2. On this theory it is unnecessary to attempt to co-ordinate the tremendous space velocities of the spirals with those of the average star.

3. The spectrum of the spirals is such as would be expected from a galaxy of stars.

4. A spiral structure has been suggested for our own galaxy, and is not improbable.

5. If island universes, the new stars observed in the spirals seem a natural consequence of their nature as galaxies. Correlations between the novæ in the spirals and those in our galaxy indicate distance ranging from perhaps 500,000 light-years in the case of the nebula of Andromeda to 10,000,000 or more light-years for the more remote spirals.

6. At such distances, these island universes would be of the same order of size as our own galaxy.

7. Very many spirals show evidence of peripheral rings of occulting matter in their equatorial planes (Fig. 37). Such a phenomenon in our galaxy, regarded as a spiral, would serve to obliterate the distant spirals in our galactic plane, and would furnish an adequate explanation of the otherwise inexplicable distribution of the spirals.

HUBBLE'S CLASSIFICATION OF NEBULÆ

Hubble's important studies of nebulæ, which were begun at the Yerkes Observatory, have been continued at Mount Wilson since 1919. One of his major tasks has been to devise a rational system of classification, which may be briefly summarized as follows:

I. GALACTIC NEBULÆ, characterized by (1) concentration about the Milky Way, (2) association with stars from which they may derive their luminosity, (3) early-type spectra, with bright or dark lines, corresponding to the spectra of these stars and (4) smooth and cloudy or wispy structure.

The two distinct types of galactic nebulæ are

(*a*) *Planetaries*, about 150 in all, of small diameter, symmetrically formed about central stars, with sharply defined edges, and showing bright line spectra.

(*b*) *Diffuse nebulæ*, some hundreds in number, cloud-like objects near the plane of the galaxy, usually associated with early-type stars. Diffuse nebulæ range from luminous to dark and from semi-transparent to opaque. They are subdivided into predominantly luminous, predominantly obscure, and conspicuously mixed.

II. NON-GALACTIC NEBULÆ, generally characterized by (1) avoidance of the Milky Way, (2) no conspicuous association with stars, (3) late-type dark line spectra, and (4) rotational symmetry about dominating non-stellar nuclei.

Non-galactic nebulæ comprise:

(*a*) *Elliptical nebulæ*, amorphous objects resembling successive stages of an original globular mass flattened by increasing rotation.

(*b*) *Spirals of two kinds, logarithmic and barred*, which appear to develop along parallel lines, the arms unwinding and the granulated structure becoming increasingly conspicuous.

(*c*) *Irregular nebulæ*, including certain non-galactic objects without central nuclei or rotational symmetry.

The planetary and diffuse nebulæ (I*a* and I*b*) do not seem to be physically related, though the planetaries may be late stages in the development of novæ (temporary stars), perhaps caused by the effect of the penetration of a star into a diffuse nebulous cloud. The spirals (II*b*) appear to have developed from elliptical nebulæ (II*a*), while the irregular nebulæ (II*c*) may have been spirals lacking dominating dynamical control.

The galactic and non-galactic nebulæ, as their names imply, differ greatly in distribution. The smallest planetaries are closely associated with the Milky Way, while the larger ones are more uniformly scattered over the sky. It is probable that their distance from the galactic plane is relatively small and that their angular diameters depend upon their distance from the earth. The diffuse nebulæ also belong to the galaxy, some of them associated with the star clouds of the Milky Way, while a second group is connected with the local cluster of

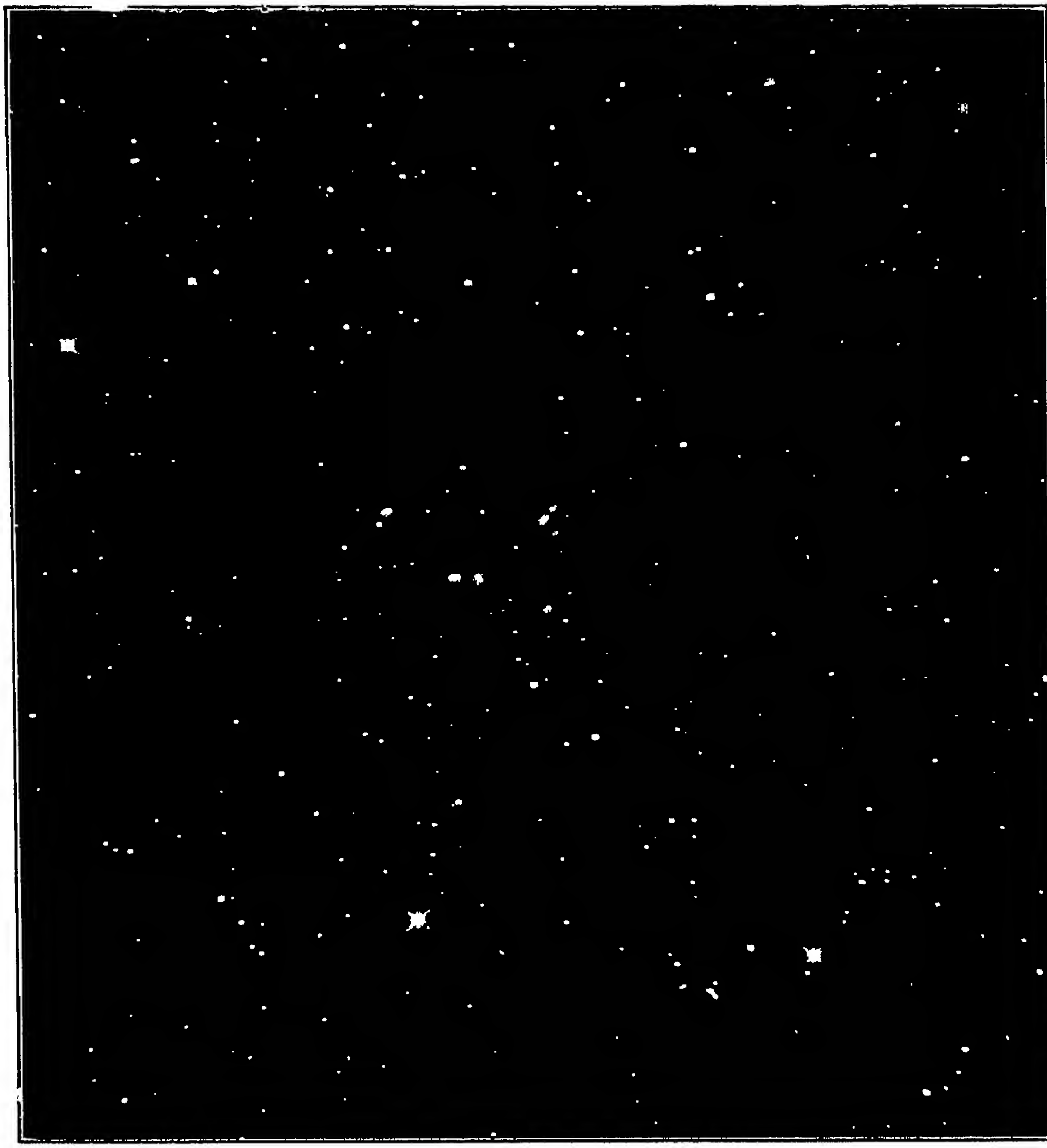


Fig. 39. Group of Small Nebulæ in Pegasus.

stars immediately surrounding the sun. Each group includes both luminous and dark objects, the luminous diffuse nebulæ in conspicuous association with very hot stars from which they derive their

light, either by reflection or by the excitation of discharged particles.

The non-galactic nebulæ, which Seares estimates to be about 300,000 in number (above a certain limiting magnitude), include a great majority of the elliptical type, though the spirals are more numerous among the bright objects. They are practically absent from the plane of the galaxy, but begin to appear about 20° from it, increase rapidly in number from 20° to 35°, then more slowly, showing a great concentration near the north galactic pole. Their distribution in longitude is very irregular.

RESOLUTION OF THE SPIRALS INTO STARS

If spiral nebulæ are distant "island universes," or isolated systems of stars comparable with our own galaxy, the larger ones may nevertheless be near enough for resolution into stars by the most powerful telescopes. The beautiful photographs published by the Lick Observatory in their superb volumes on the nebulæ and the exquisite plates taken on Mount Wilson with the 60-inch reflector by Ritchey, Pease, van Maanen, Hubble, and Humason show countless minute knots along the spiral arms of some nebulæ and many stars scattered throughout their structure. But how shall we recognize these as true stellar images, or distinguish them with certainty from the many faint stars that belong to the galaxy?

Hubble has recently answered this question in a conclusive way. Concentrating his attention upon

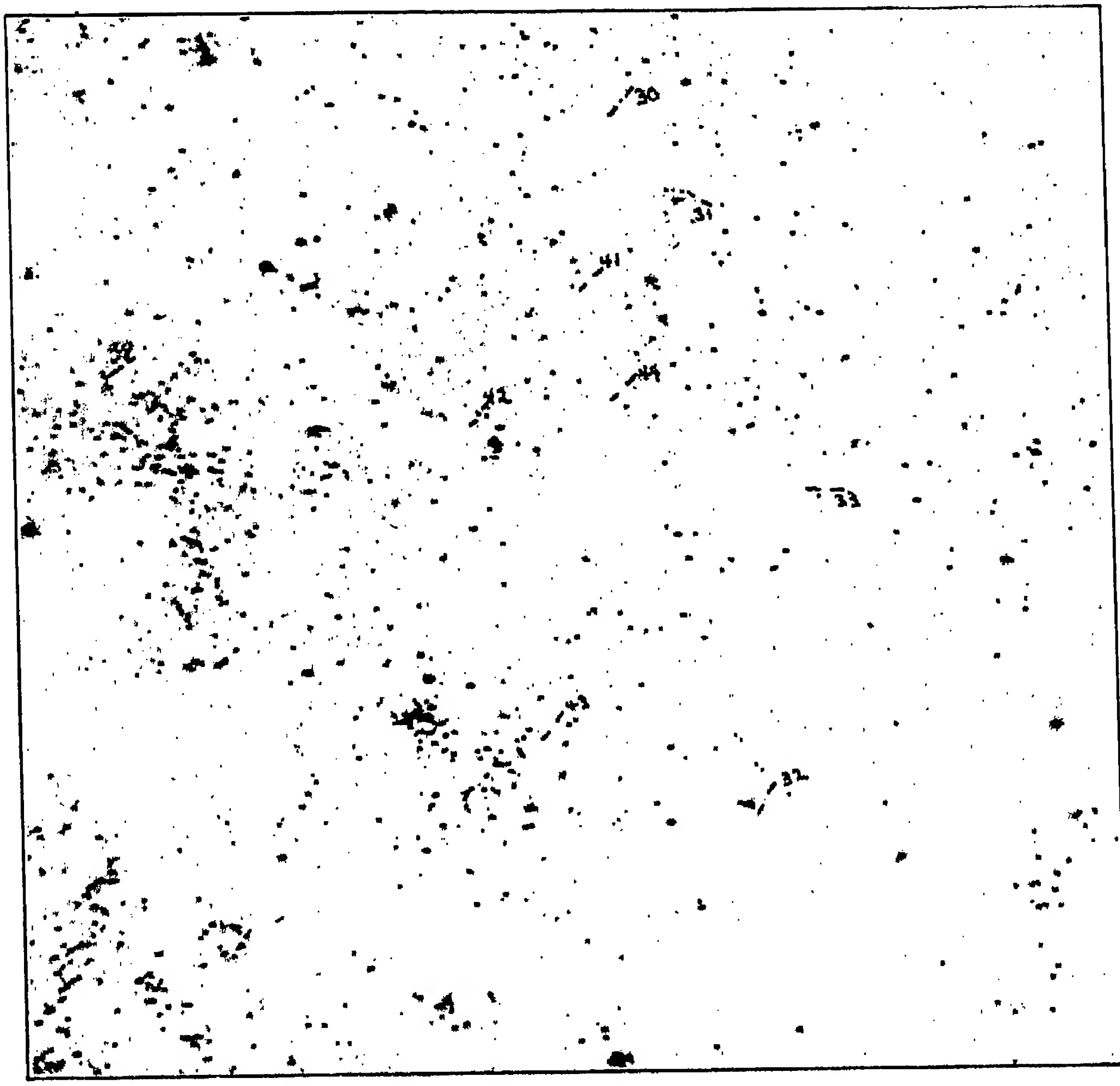


Fig. 40. Resolution of a portion of the Andromeda Nebula into stars, photographed by Hubble with the Hooker telescope. Several of the Cepheid Variables are marked on the (negative) print.

the outlying parts of such great spirals as Messier 33 and the Andromeda nebula, rather than upon the amorphous nebulosity of the central regions, he has taken a series of photographs with the 100-inch Hooker telescope for the express purpose of

determining their resolvability. These are covered with stellar images, which on a plate of Messier 33 (Fig. 40) are the smallest ever secured—only five or six tenths of a second of arc in diameter. Numerous small groups of stars on photographs of poorer definition or smaller scale merge together, and some of these are accompanied by true nebulosity, generally showing the bright line spectra of gases. Such groups, on the "island-universe" hypothesis, may be analogous to the constellation of Orion in our own stellar system, a group of stars interspersed with gaseous clouds.

Hubble's capital discovery is the detection of Cepheid variable stars in spiral nebulæ. Temporary or "new" stars had previously been observed in the great nebula of Andromeda. The most celebrated of these was the Nova of 1885, which suddenly appeared in the heart of the nebula on August 17 of that year as a star of the ninth magnitude, rose to nearly the seventh magnitude (just beyond the naked eye) by September 1, and faded to the sixteenth magnitude in the following March. Most of the novæ discovered photographically in the Andromeda nebula by Ritchey, Curtis, Humason, Hubble, and others in recent years, sixty in all, were much fainter, ranging from the fifteenth to the nineteenth apparent magnitude. But while these faint temporary stars are so numerous in the nebula that forty of them have been found by Hubble on Mount Wilson during the last three years, no Cepheid had ever been detected until Hubble identified the un-

deniable light-changes of several of these stars in the great nebula in Andromeda (M 31) and in Messier 33.

Sailors easily recognize lighthouses by the changes in brightness of their revolving lights. Astronomers

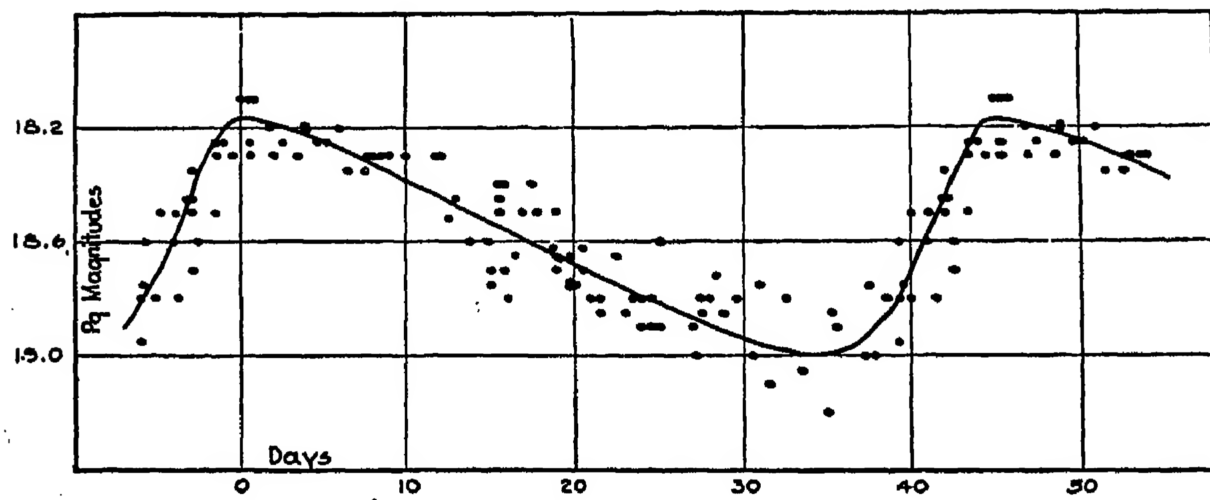


Fig. 41. Characteristic light curve of Hubble's Cepheid Variable Star No. 7 in the Andromeda Nebula.

distinguish the various types of variable stars by measuring their light-fluctuations and plotting their characteristic curves. The great nebula in Andromeda is partially resolved into stars by the 60-inch and 100-inch reflectors. Among these Hubble has already found 35 variable stars, 12 of which have the typical light-curve (Fig. 41) of Cepheids. The periods of these Cepheids range from 50 to 18 days, and their corresponding maximum brightness from 18.1 to 19.1 photographic magnitude. These results, as explained in "The Depths of the Universe," should at once give us the distance of these Cepheids, and hence of the great nebula in Andromeda.

This method of measuring distances is easily understood. Cepheid variables in the galactic system (of which the Pole Star is a well-known example) have been proved to be stars of great intrinsic luminosity, which vary in brightness because of periodic increase and decrease in diameter or perhaps because of immense periodic eruptions, resembling the eruptive prominences on the sun. The very fact that such brilliant stars are reduced in the spirals to the eighteenth or nineteenth magnitude—near the limit of observation—means that they must be at an enormous distance. Fortunately, a well-established relationship between their luminosity and light-period, effectively used by Shapley in measuring the dimensions of the galaxy, permits their actual distance to be determined. In the case of the Cepheids in the great nebula in Andromeda this distance comes out about 850,000 light-years—more than four times as far as the most remote globular cluster and well beyond the boundary of the galactic system. Other methods employed by Hubble give the same order of distance. If it is correct, the diameter of the Andromeda nebula is about 45,000 light-years, decidedly smaller than the galaxy, but quite large enough to constitute an "island universe" of very respectable size.

Another great spiral (Fig. 42) has also been found by Hubble to lie in extra-galactic space. In M 33 he has detected thirty-five Cepheids (among forty-five variable stars), and these indicate approximately the same distance as that of M 31. The an-

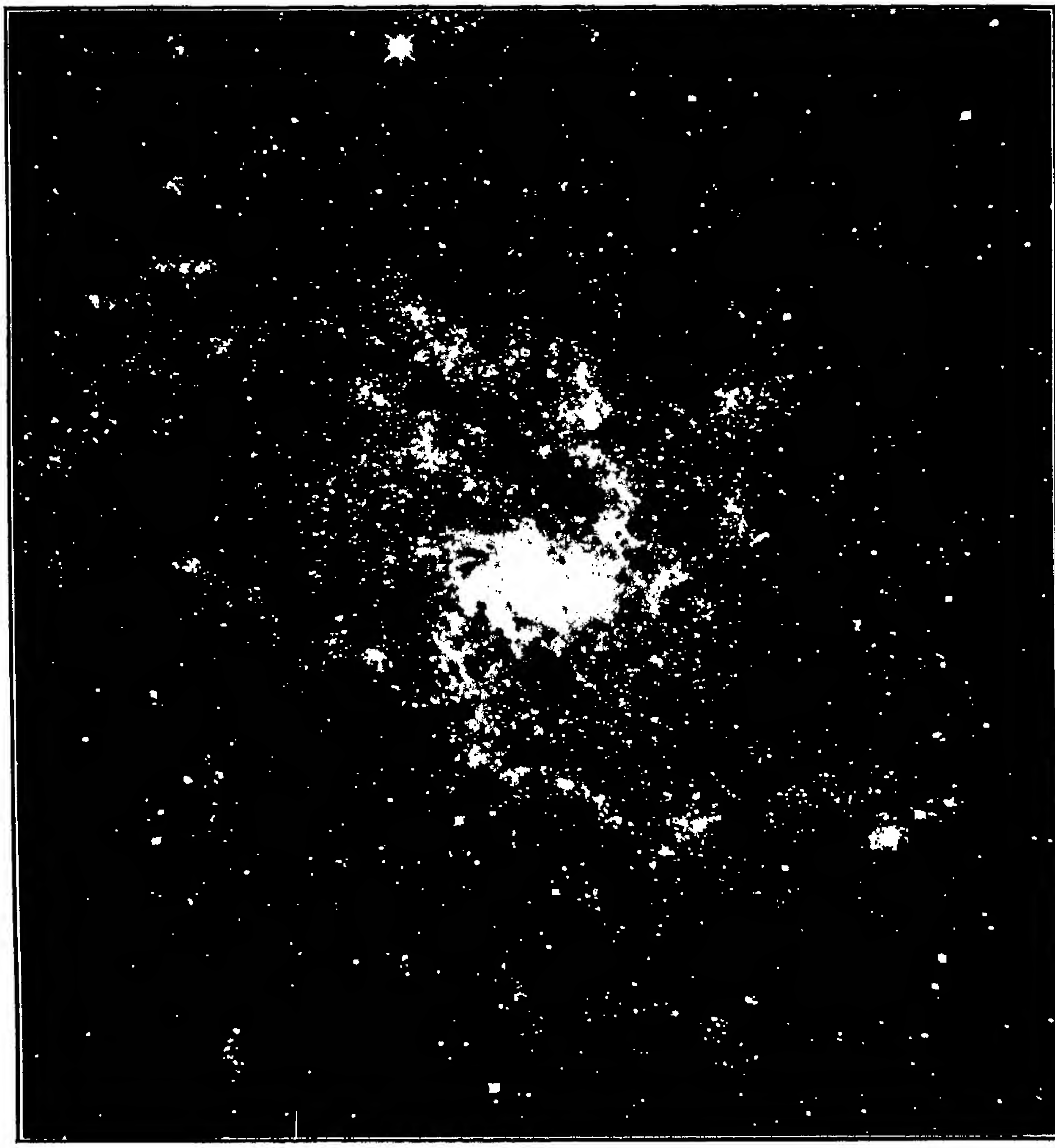


Fig. 42. Spiral Nebula M 33, photographed by Ritchey with the 60-inch telescope.

gular diameter of M 33 is one degree, as compared with three degrees for the Andromeda nebula, and its linear diameter is therefore about 15,000 light-years.

The two large spiral nebulæ thus placed by Hubble beyond the boundaries of our stellar system are not of uniform size, and both of them are smaller than the galaxy. They differ in other respects from our system, notably in the possession of conspicuous and highly concentrated nuclei. But these are details which may depend upon the stage of evolution in each case. Thus M 33 is a later type spiral than M 31, if we may judge from the increased number of condensations and the smaller amount of amorphous nebulosity.

Among the hundreds of thousands of spiral nebulæ shown on our photographs of the heavens, we should be able ultimately to detect every step in the process of their development, as we now study the life history of the stars of our own galactic system. We should also be able to determine their distribution in space. Their wide range in angular diameter, from the three degrees of the great nebula in Andromeda down to the smallest image that betrays its spiral form on photographs taken with the 100-inch telescope, suggests some such picture as Kant long ago sketched:

"If the grandeur of a planetary world in which the earth, as a grain of sand, is scarcely perceived fills the understanding with wonder, with what astonishment are we transported when we behold the infinite multitude of worlds and systems which fill the extension of the Milky Way! But how is this astonishment increased when we become aware of the fact that all these immense orders of star-worlds

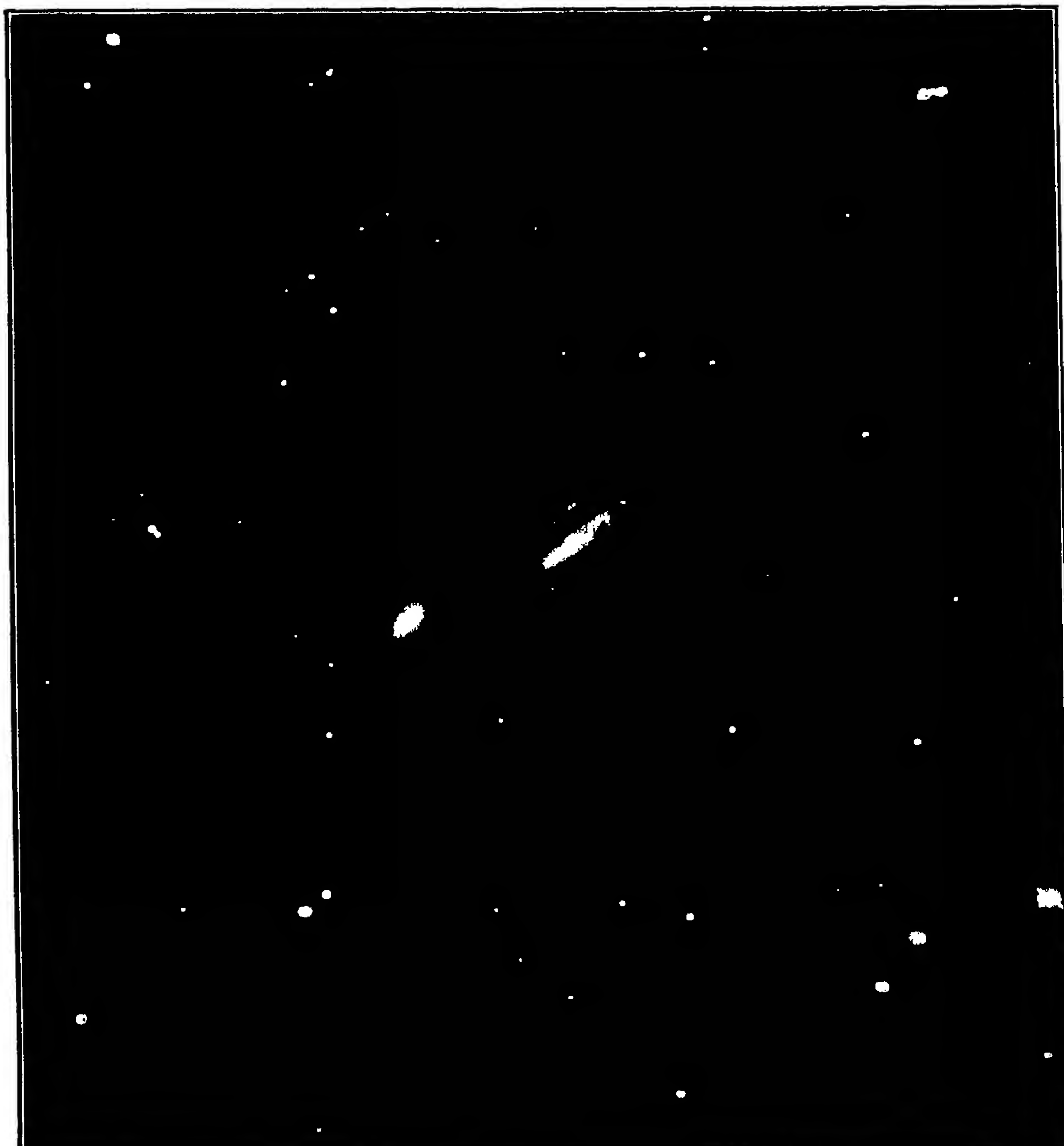


Fig. 43. Two Spiral Nebulæ H II 751–2 Bootis, photographed by Pease with the 60-inch telescope.

again form but one of a number whose termination we do not know, and which perhaps, like the former, is a system inconceivably vast—and yet again but one member in a new combination of numbers!"

It is a far cry from the facile imaginings of the philosopher to the rigorous demonstrations of exact science, and the true structure of the universe is not yet known. While Hubble's results point to the existence of hundreds of thousands of "island universes" in all stages of development, Jeans believes that "we can definitely rule out an infinite universe and the hyper-super-galaxies which have been suggested."

THE CONSTITUTION OF MATTER

One of the greatest problems of science is the constitution of matter and its conversion into radiant energy. The spiral nebulæ, remarkable as they are as "island universes," have recently assumed additional interest because of the part they may play in the solution of this problem.

Matter occurs in nature under the widest variety of composition and form. The physicist, who approaches the problem of its constitution by the most direct route, deals chiefly with the chemical elements, and evolves powerful methods of research which enable him to penetrate to the core of the atom, to visualize the electrons swinging in their orbits, and to remove them one by one for detailed study. The chemist, concerned primarily with the union of atoms into molecules, and the combination of molecules of one or more elements, attacks matter of greater complexity, extending all the way from the single atom of hydrogen to compounds containing hundreds of linked atoms of many kinds.

The astrophysicist, permitted by his telescopes to push his researches into space, observes matter in the state of luminous gaseous elements, associated in the cooler stars with certain chemical compounds. The cosmic crucibles in his celestial laboratory exhibit conditions of temperature and pressure often transcending those attainable on earth, and thus present for observation experiments on an immense scale, the interpretation of which has already added much to our knowledge of physics and chemistry.

We now know that there are just ninety-two elements in nature, the heaviest of which are spontaneously breaking up into lighter ones. The basic element, hydrogen, exists throughout the universe, accompanied by other elements in varying proportions and states. Certain stable elements can be broken up by artificial means in the laboratory, but no method of combining their constituents has yet been found. In the stars, however, there is strong reason to believe that the heavier elements are actually being built up from lighter ones, under conditions involving phenomena of radiation and absorption of energy as yet unmatched on the earth. A general study of the constitution of matter should therefore be so organized that physics, chemistry, and astrophysics may all play adequate parts.

Such a joint attack, initiated four years ago by the California Institute of Technology and the Mount Wilson Observatory, has already yielded many important results. Chief among these are Millikan's

and Bowen's contributions to our knowledge of atomic structure by their researches on stripped atoms;* recent proof by the same authors that a new non-relativistic cause—now thought to be the spinning electron—must be introduced to account for their discoveries in spectroscopy;† Seares's demonstration, in harmony with previous theoretical suggestions, that the masses of the stars decrease progressively with increasing age, indicating the gradual conversion of matter into radiant energy;‡ Adams's confirmation of Eddington's prediction that the matter which constitutes the companion of Sirius is 50,000 times as dense as water;§ and Millikan's new proof that cosmic rays, at least a hundred times more penetrating than X-rays, reach us from all parts of space.

SPIRAL NEBULÆ AS POSSIBLE SOURCES OF MILLIKAN'S COSMIC RAYS

The possibility that these remarkable new rays, capable of passing through six feet of lead, may originate in the spiral nebulæ has been discussed by Jeans in *Nature* (December 12, 1925). He had previously shown that stellar radiation is most probably due to the progressive annihilation of stellar matter, each unit (quantum) being produced by the simultaneous destruction of one proton and one

* Robert A. Millikan, "The Stripped Atom," *Scribner's Magazine*, May, 1926.
† Millikan and Bowen *Philosophical Magazine*, May, 1925.
‡ See Chapter II. § See Chapter II.

electron. Successive scattering by the particles within a star of the excessively short invisible rays thus generated would quickly increase the wave-length until it reached that of ordinary temperature radiation. Thus the stars must emit visible light and but little radiation of extremely high frequency.

Spiral nebulæ, however, must be nearly transparent to ordinary light, as the average optical thickness of the Andromeda nebula has been computed to be only about one gram of matter per square centimetre. This explains why the bright nuclear points, located at the centre of certain spirals, are visible in the telescope. Thus these spirals must be almost completely transparent to newly generated radiation, which escapes into space, with but little scattering and consequent increase of wave-length, in the form of the highly penetrating invisible rays measured at various mountain stations by Millikan.

Jeans also points out that if the spiral nebulæ are the birthplaces of stars, their power of generating radiation should be at least as great per unit mass as that of the younger stars, which is about 500 times that of the sun. But the visible radiation per unit mass of the Andromeda nebula is only about 0.16 times that of the sun. He concludes that only about one-three-thousandth part of the total radiation generated within this nebula is scattered by the nebular matter and transformed into visible light, while the remaining 2,999 parts travel through space as rays of nearly the penetrating power measured by

Millikan. He calculates that the Andromeda nebula alone might thus account for about one-half of the observed effect, the balance being due to the combined radiation of the other spirals.

This is a highly interesting suggestion, though the wave-length deduced by Jeans is smaller than that of the shortest waves observed by Millikan, and the proportion of radiation contributed by the Andromeda nebula is apparently too large. It is probable, however, that the general character of the mechanism involved in the production of the new rays has been stated by Jeans, in general harmony with the views expressed by Millikan in his first announcement:*

"But how can nuclear transformation, such, for example, as the formation of helium out of hydrogen or the capture of an electron by a positive nucleus, be going on all through space, the resulting rays coming apparently as much from one direction as from any other, and certainly not a whit more plentifully from the direction of the sun than from that diametrically opposite to it, as evidenced by the entire equality of our midday and midnight observations? The difficulty is not so insuperable, in view of the transparency even of large amounts of matter for these hard rays, combined with Hubble's recent proof at the Mount Wilson Observatory that some of the spiral nebulæ are at least a million light-years away. The centres at which these nuclear

* *Scientific Monthly*, December, 1925, p. 663. Given more fully in *Proceedings of the National Academy of Sciences*, January, 1926.

changes are taking place would then only have to occur at extraordinarily widely scattered intervals to produce the intensity of the radiation observed at Muir Lake."